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DEPARTMENT OF THE INTERIOR—U. S. GEOLOGICAL SURVEY
J. W. POWELL DIRECTOR

A NEW METHOD
OF
MEASURING HEIGHTS
BY
MEANS OF THE BAROMETER

BY

G. K. GILBERT

EXTRACT FROM THE ANNUAL REPORT OF THE DIRECTOR OF THE U. S. GEOLOGICAL SURVEY—1880-81

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A NEW METHOD OF MEASURING HEIGHTS BY MEANS OF THE BAROMETER.

By G. K. Gilbert.

CHAPTER I.

THE PROBLEM STATED.

The change proposed in this paper is of a radical nature. Since the time of Laplace the hypsometric formula he developed has formed the groundwork of all investigation and practice. Later writers have made formal modification of some of its terms and have added a term of some importance, and modern physical research has made slight corrections to the values of several of the constants he employed, but the essential features of the formula have not been changed. It is here proposed to abandon it entirely for the greater part of hypsometric work and to substitute a new formula involving none of his constants and having but a single element in common.

For more than a century the thermometer has been the constant companion of the barometer, and in nearly all the best work of recent times the psychrometer also has been called in play. The new method abandons both psychrometer and thermometer and employs the barometer alone.

Departing thus widely from the beaten path, the writer has of necessity reverted to the elementary principles upon which all barometric measurements depend, and he may therefore be permitted, if indeed he is not compelled, to preface the presentation of his method by a review of the purposes and conditions of barometric hypsometry in general.

The opening chapter is devoted to that purpose. It is believed to contain nothing either new or original, and is intended less for the practical meteorologist or hypsometer than for the general reader, to whom it is hoped it will render the succeeding chapters comprehensible. The fourth chapter, on the other hand, and those following it are addressed more especially to the student of hypsometry.

THE FUNDAMENTAL PRINCIPLE.

The principle which underlies the measurement of heights by means of the barometer is an exceedingly simple one, but its application is fraught with difficulty.

The pressure of the atmosphere upon the surface of the earth at the level of the sea is about fifteen pounds to the square inch. If one rises in a balloon or ascends a mountain he passes above successive strata of air and is relieved of their weight. The pressure he sustains at any height is that due to the weight of the air which is above him, and is progressively less and less the higher he goes. The pressure is therefore an indication of the altitude, and it is possible to acquire knowledge of the heights of different parts of the earth's surface by simply measuring the local pressures of the atmosphere. Thus, if one finds that the air imposes a pressure of $10\frac{3}{4}$ pounds to the inch of surface at the city of Quito, and a pressure of $9\frac{1}{4}$ pounds on the summit of Pike's Peak, he at once knows that there is less air above Pike's Peak than above Quito, and therefore that it is higher.

A moment's reflection will show that the diminution of pressure from the sea level upward is not simply proportional to the altitude but has a somewhat different law. The density of a gas is proportioned to the pressure to which it is subject, and since the lowest stratum of air is compressed by the weight of the whole atmosphere, while each higher stratum is compressed only by that part of the atmosphere which lies above it, the lowest is denser than any other, and there is a progressive decrease in density from the sea level upward. A A layer of air 1,000 feet deep resting on the ocean contains more matter and weighs more than a layer of similar depth at any higher altitude, and the aeronaut or mountain climber experiences a greater diminution of atmospheric pressure in ascending from the sea level to an altitude of 1,000 feet than he does in continuing his ascent from 1,000 to 2,000 feet, or through an equal space at a greater height. The loss of pressure in the first mile of ascent is 2.6 pounds to the square inch, while in the second it is only 2.2 pounds, and in the third 1.9 pounds.

The law of the relation of altitude to atmospheric pressure is therefore a logical consequent of the law of the compressibility of gases. In its simplest form it is as follows:

The difference in height of any two localities is equal to a certain constant distance multiplied by the difference between the logarithms of the air pressures at the two localities.

If the lower locality is the shore of the sea, then the difference in height deducible under the law is the altitude above sea level of the upper locality.

This relation is the foundation of all barometric hypsometry, and although its discovery was attained only by the cumulative efforts of many illustrious physicists, it is exceedingly simple. But there are a number of modifying conditions of which account must be taken in its application, and it is with these that we are chiefly concerned in this paper. Their consideration will be deferred, however, until a brief outline has been given of the means employed for the measurement of atmospheric pressures.

BAROMETERS.

The pressure on any spot of the earth's surface is equivalent to the weight of the prism of air extending upward from the spot to the confines of the atmosphere, and for convenience of discussion the pressure is conceived as being actually given by this ideal prism of air, which is called the atmospheric column.

Four distinct devices have been employed to weigh the atmospheric column. The *mercurial barometer* counterpoises against it a column of mercury, and is analogous in principle to the common scales. The *aneroid barometer* receives the pressure of the air on a metallic spring, and is strictly analogous to the spring balance. The *boiling-point apparatus* does not directly weigh the air, but merely determines the temperature at which water boils, depending for its result upon the principle that the boiling point of water is raised by increase of pressure and lowered by its diminution. The *density apparatus* is a device by which a small quantity of air is imprisoned in a tube and then compressed to a certain definite fraction of its former volume by means of a column of mercury. The height of the column of mercury necessary to do this is proportional to the original density of the air, and therefore to the atmospheric pressure by which that density is produced.

Of these instruments the mercurial barometer is both the oldest and the most accurate, and its use would be universal were it not somewhat cumbrous and easily broken. The aneroid commends itself by its convenient size and its facility of observation, and has a wide use both in reconnaissances and as an adjunct to the mercurial barometer in geographic surveys, but it is too delicate a piece of mechanism to be entirely trustworthy. The boiling-point apparatus is in many cases preferable to the aneroid barometer for independent use, but is nearly superseded by the mercurial. The density apparatus is probably not in use.

The construction of the mercurial barometer is essentially as follows: A glass tube about three feet in length and closed at one end is filled with mercury and then inverted with the open end immersed in a cup of mercury. A portion of the mercury flows from the tube to the cup, and a space is left in the upper (closed) end of the tube. This space is a vacuum, air having no access. The mercurial surface in the tube, having mere vacuity above it, receives no pressure, while the surface in the cup bears the full pressure of the atmosphere, and as a consequence the mercury stands higher in the tube than in the cup. The difference in level between the two surfaces is the height of the column of mercury necessary to counterpoise the weight of the superincumbent air. A column of mercury two inches in height imparts a pressure of about one pound to the square inch, and a column of about thirty inches is accordingly necessary to counterbalance the fifteen pounds of atmospheric pressure at sea level. When, therefore, the barometer is placed

near the sea level, the height of the mercury in its tube is about thirty inches above the surface of the mercury in its cup, or, in familiar parlance, the "height of the barometer" is thirty inches. The use of the mercurial barometer is so general that the pressure of the air is ordinarily described by means of the linear measures of its scale instead of by weights—the Englishman and American speaking of inches of pressure and the continental European of millimeters of pressure.

The many forms which have been given to the barometer need not be described here. The cup in which the tube is inverted is ordinarily called a "cistern," and is permanently attached to the tube. A graduated scale, usually of brass, is fastened in close juxtaposition to the tube and the height of the column is ascertained by comparing it with this scale.

A thermometer is also attached, so that the temperature of the mercury of the column and of the brass of the scale may be known. This is rendered necessary by the different expansibility of the two substances under the influence of heat. On a warm day the mercury rises higher along the scale than on a cold one, the air pressure remaining the same.

An observation of the barometer consists, therefore, of two parts: first, a reading of the height of the mercury; and, second, a reading of the temperature of the instrument. A correction is then applied to the mercurial height, so as to give it the value it would have at the standard temperature.

A second correction takes account of the difference in the force of gravity at different places, and becomes necessary because the heaviness of mercury is proportional to the local force of gravity, so that the same absolute air pressure is at different places recorded by mercurial columns of different heights.

The essential part of an aneroid barometer is a thin drum of elastic metal from which the air has been exhausted. The heads of the drum are bent inward by the pressure of the air, the pressure being counterpoised by the elasticity of the metal. With augmentation of pressure the inbending is increased, and by relief from pressure it is diminished; while by a system of levers the movements of the flexed heads are (in most instruments) communicated to an index traversing a dial. The amount of motion imparted to the index by the addition of a unit of pressure depends not only on the arrangement of the levers, but on the form, thickness, and elasticity of the drum-heads, and cannot be precisely foretold for any individual instrument. In order to ascertain it, the movements of the index are compared with those of the column of a mercurial barometer exposed to the same pressures, and the dial is graduated accordingly. The spaces on the dial are given the same name as the units of the mercurial scale, although they have not the same linear dimensions.

The aneroid barometer is thus adjusted in the process of its construction so that its indications accord with those of the mercurial, and it theoretically accomplishes the same results with great economy of time

and care; but it is usually found in practice that aneroids subjected to the vicissitudes of travel, and especially of mountain climbing, do not maintain their adjustment. It has therefore become the custom in most surveys to use the instrument only in a dependent way, comparing it at short intervals with a mercurial barometer so as to keep account of the amount and variation of its error. Thus checked it renders important service.

MODIFYING CONDITIONS.

Returning now to the consideration of the relation between local pressures of the atmosphere and local altitudes, we will give attention to the conditions which modify the application of the general law.

The most important of these is temperature, for the density of air varies through a wide range in response to changes of temperature. If the pressure of the air be measured by a barometer in the car of a balloon, and at the same time by another barometer on the ground beneath it, the difference between the two quantities denotes the pressure imposed on the ground by that portion of the atmosphere beneath the balloon, or, as more commonly expressed, it denotes the weight of the column of air between the balloon and the ground. The weight of that column depends on its height and its density. Its density depends primarily on the pressure of the superincumbent air, as indicated by the barometer in the balloon, but it depends also on the temperature of the column itself, being greater if the air is cold than if it is warm. In order, therefore, to compute accurately the altitude of the balloon above the ground, it is necessary to know the temperature of the intervening air column as well as the pressure above and below, and it is of course necessary to know the law which governs the expansion of air in response to the acquisition of heat. In the various formulas which have been employed for the computation of altitude a term has been written to express the influence of the temperature of the air upon the result, and this has been conjoined to the principal term which expresses the relation of heights to pressures. The pressure term is adjusted to the supposition that the temperature of the air is that of freezing water, and the temperature term appears as a correction proportioned to the difference between the actual air temperature and the freezing temperature. For each thousand feet of altitude the correction amounts to two feet (approximately) for every degree of the Fahrenheit scale.

The factor of next importance depends on the humidity of the air column. The atmosphere is essentially a mixture of oxygen, nitrogen, carbonic acid, and aqueous vapor. The proportions of oxygen and nitrogen are practically constant; the quantity of carbonic acid is more variable, but is too small to be considered here; the amount of aqueous vapor is both large and variable. We may, for the present purpose, regard the

whole as consisting of two parts, dry air and aqueous vapor, the dry air being a constant homogeneous gas mixture and the aqueous vapor a variable accessory.

Dry air retains permanently the gaseous form but aqueous vapor does not, and upon this difference depends the variability of their mixture. The tension or expansive force of dry air increases in a definite way when its volume is diminished by extraneous pressure, and also when its temperature is raised; its tension is diminished by increase of volume and fall of temperature; and these properties subsist under all pressures and at all temperatures to which the atmosphere is subject. Aqueous vapor follows the same law, but only within a certain range of conditions. For each temperature there is a certain tension which cannot be exceeded, and for each tension there is a certain limiting temperature; and when these limits are passed a portion of the vapor is condensed. The circulation of the air continually varies the conditions to which its aqueous vapor is subject, now causing a part to be precipitated, and again permitting an additional quantity to be absorbed from the ocean or from moist surfaces of land.

If the densities of dry air and aqueous vapor were identical for the same tension—*i. e.*, if the two gases were equally heavy—the ratio of their mixture would not affect the measurement of heights; but aqueous vapor is only five-eighths as dense as dry air, and the density of the air column weighed by the barometer depends therefore in part on the ratio of its contained vapor.

Accurate hypsometry accordingly demands that some account shall be taken of the aqueous contents of the air, and a humidity term has been given place in many formulas for the computation of altitudes.

There are other small factors dependent on the inequality of the force of gravity at different latitudes and at different altitudes, and the consequent inequality in the weight of air, which need not be specified here. For the purpose of the present discussion the difference in altitude of two barometric stations may be regarded as depending on the air pressures at the two stations and the temperature and humidity of the intervening air column.

With the outlines of the subject now before us, the difficulties which bar the way to the attainment of results of the highest accuracy may be stated. They arise from the fact that the air is never in a state of static equilibrium but is perpetually undergoing local changes of pressure, temperature, and humidity. If those changes were uniform, or uniformly periodic, it would not be a hopeless task to take full account of them and eliminate their influence from the hypsometric problem; but they are irregular in a high degree and they spring from causes so complex that their thorough analysis appears impossible.

Consider for a moment how many things conspire to give diversity to meteoric changes. In the first place, the sun, which is the ultimate source of all disturbance, shines only by day. While it shines, a certain amount of heat is imparted to the whole atmosphere, but a much higher

temperature is given to the ground and is communicated to the contiguous layer of air. At night the atmosphere loses heat by radiation to space, but the ground loses it still more rapidly and imparts its low temperature to the lowest stratum of air. The lower strata, therefore, have exceptional warmth by day and exceptional coolness by night. If the air is moist it intercepts a greater quantity of solar heat than if it is dry, so that a less quantity reaches the ground; while at night atmospheric moisture checks radiation from the ground. The power of the earth's surface to receive or store or part with heat varies with its character. Naked rocks and cultivated fields, bare earth and grass, forest and snow, are affected very differently by the heat rays of the sun and exert equally diverse influences on the adjacent air, so that one tract of land is often in a condition to heat the air while an adjacent tract is cooling it. Then, too, the sun's heat is unequally distributed through the year; outside the tropics there is a progressive accumulation of heat through summer and a progressive loss through winter. The circle of the seasons thus produced reacts on the surface of the land, causing verdure, barrenness, and snow in alternation; and these in turn have their influence on the local meteoric changes.

The ocean undergoes less change of temperature than the land and its rate of change is slower, so that there is frequent, and indeed almost continuous, contrast of condition between it and the contiguous land.

In many places this contrast is heightened by oceanic currents (born, like air currents, of the sun's rays), which perpetually convey warm water to cold regions and cold water to warm regions.

As a result of all these influences, together with others that might be enumerated, the equilibrium of the air is constantly overthrown and the winds, which tend to readjust it, are set in motion. If a condition of static equilibrium were possible, we may suppose that the whole atmosphere would become a uniform mixture or else one varying according to a simple law, and that it would be arranged in a system of horizontal layers, each one of which would be denser than the one above and rarer than the one below and would have a uniform temperature throughout. But in reality its temperature is continually modified by external influences; the static order of densities is broken and currents are set in motion; and the circulation and the inequalities of temperature conspire to produce inequalities of moisture. Every element of equilibrium is thus set aside and the air is rendered heterogeneous in composition, temperature, and density. Moreover, the disturbing factors are so multifarious and complex that there is infinite variety of combination and infinite variety of result. Nothing can be more fickle than the weather, and the weather is merely the totality of atmospheric states and changes viewed in relation to human activities.

The complete solution of the problem of barometric hypsometry is thus rendered impossible, or if not impossible at least impracticable, since, if our knowledge is ever equal to the task, the expense of the solution in any individual case cannot fail to be greater than that of deter-

mining the desired altitude by means of the engineer's level. Approximate solutions only are expected, and ever since the development of the general theory the ingenuity of investigators has been directed to the restriction and limitation rather than to the abolition of errors.

Although the disturbing factors all spring from the same remote source, and although they react upon each other in the most intricate way, it is nevertheless possible, when series of observations are compared, to discriminate many of them, and it has been found that every added refinement of analysis has led to new devices for the elimination of error. A discussion of hypsometric methods should therefore be prefaced by a classification of disturbing factors.

GRADIENT.

Designate by A and B two stations at the same altitude. With the air in a state of static equilibrium each receives the same atmospheric pressure; but when the equilibrium is disturbed one may receive more than the other. If A has a greater pressure than B there is a tendency of the air to move in the direction from A to B until equality of pressure is attained. Add now a third station, C, forming with the others a horizontal triangle, and conceive verticals to be erected at each of the three, proportioned in height to the local pressures. A plane passing through the summits of the verticals will evidently be inclined in some direction (unless the pressures are equal) and this inclination is called *barometric gradient.* The direction toward which the plane inclines is called the direction of the gradient. In other language, the direction of the barometric gradient at any point is the direction toward which there is the most rapid decrease of pressure.

The contour lines drawn on the weather maps published by the United States Signal Service are lines of equal pressure (*isobars*). If lines of gradient were also drawn on one of these maps, each gradient line would pass from an area of high pressure to a center of low pressure in such way as to make a right angle with each pressure contour at the point of intersection.

There is another point of view which will perhaps help to a clearer understanding of the matter. Suppose that of a large number of stations on a plain, A is the one with the lowest pressure at a given time. At any other station, B, the pressure is somewhat greater, but by ascending in mid-air we can find a point, directly above B, where the pressure is precisely the same as at A. So above every point of the plain we can find a corresponding point with the standard pressure, and the combination of all these points constitutes an ideal surface of equal pressure. With the atmosphere in equilibrium such a surface would be level, but in point of fact it is ever undulating. Its inclination at any point is the barometric gradient, its direction of inclination is the direction of gradient, and its degree of inclination measures the amount of gradient.

The standard of pressure assumed in the preceding paragraph is entirely arbitrary, and it is evident that any atmospheric pressure whatever could have been assumed. We can in imagination project through the air a surface containing all points which have a pressure of 30 barometric inches, and another surface containing all points with a pressure of 29 inches, and indeed any number of similar surfaces. In the hypothetic case of atmospheric equilibrium all such surfaces would be both level and parallel, but in the actual case of disturbance and motion none are level and no two are precisely parallel. When widely separated surfaces are compared the variations from parallelism are often so great that their inclinations above the same locality have opposite directions. The atmospheric gradient at the surface of the ground may therefore differ greatly in amount and direction from the simultaneous gradient at a considerable altitude above the same spot.

The importance of the hypsometric difficulties introduced by gradients will be readily understood. It almost never happens that two points to be compared in altitude are in the same vertical line, and whenever they are not their barometric relation involves a factor of gradient. Suppose that barometers have been read simultaneously at *A* and *B*, (Fig. 27) and it is desired to ascertain their difference of altitude. *B C* is a horizontal line, and we will suppose *B D* to give the local profile of

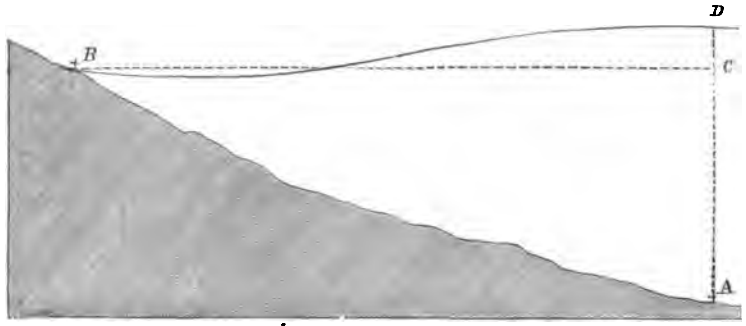


FIG. 27.—Diagram to illustrate atmospheric gradient.

the surface of equal pressure passing through *B*. If we know the density of the air column above *A*, we can compute from the barometric readings the height (above *A*) of a point (*D*) having the same pressure as the point *B*; but what we really desire is the altitude of the point *C* on a level with *B*, and in order to pass from one to the other we must know the gradient.

Variations of gradient are for the most part the result of conditions so complicated that in the present state of meteorologic science they have to be classed as irregular, but there are two elements of variation which are strictly periodic and have been the subject of much research; one has a daily period, the other a yearly. Changes of gradient may therefore be classed as diurnal, annual, and non-periodic.

Diurnal gradient.—It is a fact familiar to meteorologists that the pressure of the air everywhere undergoes a daily oscillation, being at

a maximum soon after sunrise, and at a minimum some hours before sunset, besides exhibiting other maxima and minima. The amount of change is relatively great at the equator and diminishes toward the poles. It is greater in summer than in winter, and it is usually greater in valleys and on plains than on mountain peaks. It is subject, moreover, to variations in character as well as variations in magnitude, and changes of altitude are often accompanied by conspicuous variations in character. The differences which pertain to latitude and to season do not affect the ordinary hypsometric problem, but differences depending on the altitude have a notable influence. The geographer frequently undertakes to determine the height of a mountain by comparing the pressure at its summit with the pressure at its base, and since the diurnal oscillation of pressure is not the same at base and summit an error is introduced into his result. Usually his result is rendered too large in the forenoon and too small in the afternoon, but to this rule there are exceptions; and it is probable that the error cannot be thoroughly eliminated without a knowledge of the nature of the diurnal change at each station.

Annual gradient.—The annual oscillations are variations of what may be called the perennial system of gradients. Since the atmosphere if undisturbed would have no gradients, and since every disturbance produces them, it is easy to understand that any continuous disturbance will be accompanied by permanent gradients. The excess of solar heat received in the tropics, as compared with the polar regions, is of the nature of a continuous disturbance, and sets in motion the great currents of the atmosphere. Warm ocean currents flowing toward the poles, and cold ocean currents flowing toward the equator, are other disturbing elements of a continuous nature, which modify the great air currents in a uniform manner. Under the joint action of these causes the great system of the winds is instituted, and coincident with it a great system of permanent gradients. The annual progress of the sun from tropic to tropic throws a preponderance of heat first on one side of the equator and then on the other and produces an annual cycle of changes both in the great winds and in the permanent gradients.

Non-periodic gradients are caused by the multifarious local agencies and accidents which give rise to variable winds and to storms. They are ordinarily so great and their variations are so rapid that they completely mask, so far as hypsometry is concerned, the perennial and annual gradients—at least in the temperate zones. They do not, however, obscure the diurnal changes to the same extent.

It is necessary, therefore, for accurate determination of altitude by the barometer to take account of the non-periodic gradient and of that gradient which has a daily period. The former is involved in the general air movements of the region at the time of observation; the latter bears some relation to the topographic characters of the points of observation as well as to the hour of observation and the time of year.

DEVICES FOR THE ELIMINATION OF ERRORS DUE TO GRADIENT.

The most important of all the devices which go to make up the barometric method in use consists in the employment of a base station. If the pressure at the shore of the sea were uniform it would be necessary for hypsometric purposes to measure the atmospheric pressure only at the point whose altitude is desired, for that measurement would afford at once the differential pressure and, consequently, the weight of the differential air column. In fact, however, it is not uniform, but fluctuates greatly from week to week, and even from hour to hour, and it is therefore important that we know its amount at the time when the pressure at the higher point is measured. Moreover, since gradients of the non-periodic order often slope continuously in the same direction for hundreds of miles, it follows that we shall diminish the probability of error if we use as the standard for each comparison that point of the coast nearest to the point to be determined.

It is not essential, however, that the point used as a standard—*the base station*—be either at or near the shore, provided only its altitude is known; and if it can be established in close proximity to the point to be measured the effect of non-periodic gradient is nearly avoided.

The intelligent geographer who uses the barometer for the determination of altitudes pursues the following plan: He selects some point either within or near his field of survey for a barometric base station. The height of this point is determined with great care, either by means of the surveyor's level or by means of a series of barometric observations made coincidently with a similar series at some point of known altitude and continued for a long time. Having placed a barometer and observer at the base station he carries another barometer to the points to be determined—called *new stations*—and makes synchronous readings; that is to say, he so arranges the time of observing the barometers that each reading at a new station shall be simultaneous with a reading at the base station. In the subsequent computations only the pairs of synchronous observations are used. By establishing the base station in close proximity to the new stations, the error arising from non-periodic gradient is in great part avoided. By synchrony of observation the results are protected from such errors as might arise from progressive increase or decrease of pressure in the district during the time elapsing between observations not synchronous.

It is evident that the use of the base station excludes from the observations a portion only of the gradient which would otherwise enter, and affords no means of eliminating from the results the error wrought by the remainder. It is often impracticable to place it so near the new station as to render the included gradient insignificant in amount, and it is therefore important to have corrective means at hand.

Two corrective methods are known, although up to the present time one only has been widely employed, namely, the method by long series. Since the non-periodic gradient is produced by a variety of discontinu-

ous causes, it is assumed that it will in the long run favor one direction no more than another, so that the sum total of its influence through a long period will be approximately zero. An extended series of observations, therefore, covering several weeks or months, affords a mean result superior in accuracy to the result from a single pair of observations. The gain in accuracy, however, is usually incommensurate with the attendant expense, and the method is practically resorted to only when some other purpose is at the same time subserved by the observations.

The second method involves the actual determination of the included gradient and demands the employment of at least three base stations. These should be established at approximately the same altitude and in such relative position that the lines joining them shall include the principal portion of the district of new stations. The pressures at the three stations at any point of time afford the means of computing the coincident direction and amount of the gradient on the assumption that the surface of equal pressure, to which reference has already been made, is an inclined *plane*, without curvature. This assumption is never strictly warranted, but if the district is small as compared with the amplitude of the pressure waves which cross it no serious error is involved. The general direction and rate of gradient having been computed, a similar calculation shows how much exists between the new station and that base to which it is referred for the computation of altitude. Its amount is then applied as a correction to the reading at that station.

The same result may be attained more easily and with a sufficient degree of accuracy by applying a graphic method to the same data. The new station, the base stations, and the simultaneous pressures at the base stations being marked on a map, it is a simple matter to draw across it, by eye estimate, contour lines of equal pressure (isobars), and so soon as this has been done the amount of the correction appears by inspection.

The expense of maintaining a number of base stations is a serious objection to this method; but if the accessory stations have other functions, so that the hypsometric work does not have to incur their cost, their practical utility can hardly be doubted. In any country furnished with weather maps such as the thrice-daily series of the United States Signal Service the hypsometer is provided with gradient corrections graphically presented and without expense.

There is one class of non-periodic gradients to which the preceding method will not apply—namely, the gradients accompanying thunder storms and other restricted vortical movements. The assumption that the surface of equal pressure is plane, even for a small district, is in this case so erroneous that isobars cannot be used. If the local effect of the disturbances upon the barometer is indicated by a continuous series of observations made at short intervals, it is sometimes thought best to plot the observations on section paper in such way as to represent the rise and fall of the barometric column by an ascending and descending curve and then graphically replace it by a smoother curve assumed to express the movement which would have taken place but

for the exceptional disturbances. In the illustrative diagram the vertical lines represent hours and the horizontal lines hundredths of an inch of pressure. The curved line shows the oscillations of pressure on a day characterized by thunder storms, and the broken line shows the pressure curve as arbitrarily amended. The amended pressure is substituted for the observed in the computations of altitudes. When such disturbances are known to have occurred at the new station or base station and the observations are not sufficiently full to permit their elimination, the best practice is to discard the observations and base no determinations upon them.

The method by plotted isobars has a theoretic advantage over that by long series, in that it takes account of the perennial gradient as well as the non-periodic. It affords a correction for the actual gradient at the moment of observation, without reference to the elements of which that gradient is composed; while the method by long series eliminates errors only by balancing those with a positive sign against those with a negative, and necessarily fails to expunge constant errors. In order, however, to render practical this advantage in the use of isobars it is essential that the altitudes of all the base stations shall have been measured by the spirit level, for if measured barometrically, no matter with what precautions, they will themselves be liable to an unknown correction for perennial gradient.

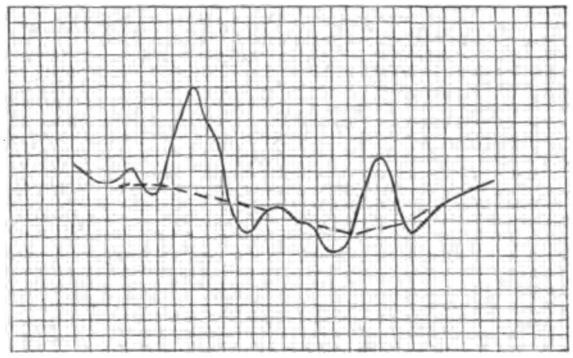


FIG. 28. Diagram to illustrate the Graphic Method of Correcting Barometer Readings made during a Thunder Storm.

On the other hand, the method by long series has a theoretic advantage over that by plotted isobars, in that it takes account not only of gradients but of the non-parallelism of gradient planes. When the new station is several thousand feet higher than the base stations from which isobars are plotted, it not unfrequently happens that the surface of equal pressure passing through it has a very different form and inclination from the surface of equal pressure passing through the lower stations, and the hypsometric error due to this want of parallelism entirely escapes the method by plotted isobars.

Circumstances sometimes arise in which, while it is impossible to apply corrections for non-periodic gradient, it is nevertheless practicable to enhance the value of the result by discriminating among the individual observations of a short series—giving little influence to

some or rejecting them altogether. Nearly all non-periodic gradients are associated with broad cyclonic movements of the air, and whenever this is true their relation to the local wind is somewhat definite; the steeper gradient accompanies the stronger wind, and observations made during a strong wind have therefore a relatively low value. To this rule, however, there are exceptions; in all ordinary cases the direction of the isobaric contour passing through a station can be inferred from the direction of the wind, and whenever it appears that the base and new stations fall under the same isobar, non-periodic gradient need not be feared.

Turning now to the diurnal variation of gradient, we find four methods in use which serve to diminish its influence. It has already been explained that the pressure of the atmosphere everywhere undergoes a daily cycle of change in addition to its other changes, and that the daily cycles of different localities are different. It is especially true that the changes occurring in valleys differ from those on peaks or even on hills. If the cycle at the base station is the same as at the new station, no gradient arises, because the *relative* pressure is unchanged; but if the cycles are unlike, differences of relative pressure occur, and such differences are gradients affecting the hypsometric result. A gradient of this sort varies from hour to hour and is inclined alternately toward the base station and the new. At the instant of changing its direction it ceases altogether, and if that instant can be selected for the observation the error is avoided. One method of escape from the difficulty consists, therefore, in the selection of the most favorable hours for reading the barometers. A great deal of attention has been given to the selection of favorable hours, not indeed with reference to the particular error arising from diurnal gradient, but with reference to the sum total of errors affecting barometric measurement of altitude. There are two serious objections to the employment of hour selection as a corrective for this particular error. The first is that the propitious moment is earlier on some days than on others, even in the same locality and in the same season of the year, while the change of gradient is usually most rapid just as it passes its zero. A small deviation in time would therefore frequently occur and would result in the introduction of a considerable element of gradient. The second is that the favorable moments are not the same for different pairs of stations; so that without a more thorough understanding than has heretofore been attained of the dependence of particular types of diurnal oscillation on the peculiarities of locality, it must be impracticable to lay down any general and useful rule for the selection of times of observation—at least as applied to the elimination of errors of this class.

The second and most obvious method is to ascertain the diurnal cycle of each station and apply to each observation a correction reducing it to the value it would have if there were no diurnal pressure change.

Suppose, for example, that we wish to compute the relative altitude

of Ogden, Utah, and Pioche, Nevada, and have among our data the pressures at the two stations at 1 p. m. on the 1st of October.

Pressure at Ogden=25.502 inches.
Pressure at Pioche=24.221 inches.

Curves exhibiting the pressure cycles (diurnal barometric curves) for those stations at that season of the year have been published by Marshall,* and from them we learn that at one o'clock the pressure at Ogden is .019 in. greater than its mean for the day, while at Pioche it is .004 in. less than the mean. The observed pressure at Ogden is therefore diminished by way of correction, and that at Pioche is increased, and the corrected pressures—

$$25.502-.019=25.483, \text{ and}$$
$$24.221+.004=24.225,$$

are used in the computation of the desired altitude.

It is an objection to this method that its application to a single station is expensive. Except at maritime stations near the equator, the daily cycle of pressure is so combined with non-periodic changes that it is necessary to make a series of observations extending through several days in order to obtain data to separate it,—an outlay of time ill compensated by the advantage gained. It may be said also that while the observations to determine the pressure curve must extend through several days, a series comprising only a single day will afford a mean value of the pressure for that day which can be used directly in the computation with superior advantage. This consideration is so obvious that in practice observations for the diurnal curve at a station are never made for the purpose merely of aiding in the computations of altitude for that station. There is a general belief, however, that the diurnal pressure cycles of all stations in the same district which have approximately the same altitude are so nearly identical that one may be substituted for another, and that it is therefore possible to ascertain the character of the oscillation at one station of such a group and assume it for the others. In this way an obvious economy is effected where many new stations are to be determined, and if the belief is well founded it is possible, by classifying all the new stations of a survey in groups and determining the diurnal oscillations for each group, to prepare a system of corrections which will practically rid the observations of diurnal gradient. It is to be feared, however, that the belief is not warranted, for recent investigations tend to show that the local peculiarities of diurnal cycles depend as much upon the topographic peculiarities as upon the altitudes of their localities, so that any grouping based purely upon altitude would be fallacious and misleading.

The third method consists in selecting a base station within each group of new stations and referring all stations of that group to it in

* U. S. Geog. Surveys W. of the 100th Mer., vol. ii, pp. 544, 545, and Plate IX.

the computation. The diurnal curves of new and base station being hypothetically identical, no diurnal gradient exists and no correction is needed. Being based upon the same assumption as the last method it is open to the same objection, and the great expense of using a base station for each similar group of new stations would effectually prevent its use if no object were to be attained aside from the elimination of diurnal gradients. There are, however, other and more important advantages to be gained by such a multiplication and vertical distribution of stations, as will presently appear.

In the fourth method series of observations are made at the base and new stations for twenty-four hours, and the means of these series are employed in the computation instead of the individual observations. It is probable that the effect of diurnal oscillation is completely eliminated by this procedure,—it is at least impossible to distinguish from non-periodic gradient any residual gradient which may exist. The sole objection to the method is its expense, but this so far outweighs the object to be attained that it is rarely resorted to.

It is easy to conceive that other means of dealing with diurnal gradient might be devised which would be at the same time effective and economically practicable if only we were possessed of a satisfactory theory of the proximate cause of the diurnal pressure change. The subject has long occupied the attention of meteorologists and hypsometers, and a number of tentative theories have been advanced, but while it may be possible that some of these contain the essence of the true explanation it must be admitted that no one of them has commanded general assent and recognition. Like every other change affected by a daily period, it finds its remote cause in the heat of the sun, but the explanation of its immediate genesis as a result of the daily movements of the atmosphere has proved a baffling problem in atmospheric dynamics. It is to be feared that even after its general theory has been established there will remain great difficulty in the determination of the influence of local geographic conditions.

TEMPERATURE.

It has been explained in a preceding section that gradients are caused initially by inequalities of temperature, and it is equally true that fluctuations of humidity are more or less remotely dependent on changes of temperature; so that the temperature factor is indirectly responsible for a large share of the difficulties which encompass the barometrician. Unfortunately it is directly responsible for the remainder, and the errors of which it is the immediate cause are, on the whole, the most serious of all. They arise from the heterogeneity of air with respect to warmth, and from the practical difficulty of ascertaining the thermic condition of the column of air which is weighed by the barometer. Not only is the

greater part of the column inaccessible to us, but that portion to which our observations are restricted is the portion least representative of all.

Having recourse once more to a diagram, let *A* and *B* be two stations at which barometric and thermometric observations have been made and of which it is desired to ascertain the difference in altitude. Let us assume that the difficulties dependent upon gradient have been overcome, so that the atmospheric pressure is known not merely at *B* but at the point *C*, having the same altitude as *B* but situated vertically above *A*. In order to complete the computation it is necessary to know the temperature of the column *A C*. If the atmosphere were in a condition of static equilibrium there would be a uniform gradation of temperature from *C* to *A*, and the mean temperature of the column would be expressed by the half sum of the temperatures at *B* and *A*. In the "hypsometric formula," as it is called,—the formula which expresses the general relations between heights, pressures, temperatures, and moistures, and

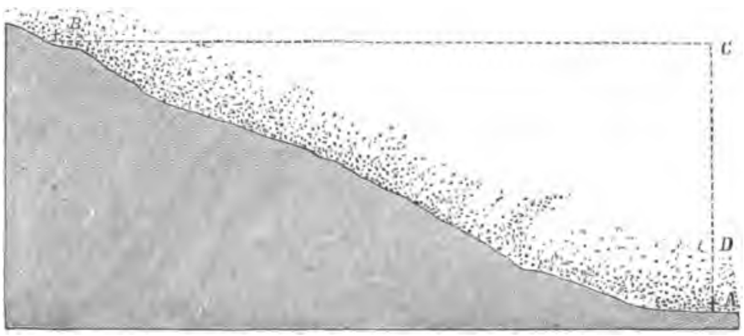


FIG. 29.—Diagram to illustrate the Thermic Inequality of the Atmosphere. The Dots indicate the Region of Most Rapid Change.

which forms the groundwork of all hypsometric computation,—a static condition of the atmosphere is postulated, and this half sum is assumed to give the temperature of the included air column.

How inadmissible this assumption is will appear at once when the manner in which the air acquires and loses heat is recalled. The body of the atmosphere is heated directly by the sun and gives off its heat by radiation to space. The surface of the earth is heated and cooled in the same manner, but many times more rapidly, so that by day it is always much warmer than the body of the air, and by night it is much cooler. A layer of air next the earth receives its warmth from the earth, and is thereby caused to differ widely in temperature from the remainder of the atmosphere.

In middle latitudes the average range of the daily temperature oscillation of the body of the air is about 4°F.*, while for the superficial

* The daily range of the temperature of the body of the atmosphere is not known by direct observation, but indirectly through computations of altitude. When a long series of observations at two stations are combined so as to show the mean pressure, mean temperature, and mean humidity at each station for every hour of the day, and

layer it is from 10° to 20° near the sea-shore, and from 20° to 35° in the interior of continents. Usually therefore there are but two moments in the twenty-four hours when the temperature of the air near the ground bears a normal relation to that of the mass of the atmosphere above; in the night it is many degrees too cool, and in the heat of the day it is many degrees too warm.

Unfortunately for the art of barometric hypsometry, the general temperature is the one most important to know, while it is practicable to measure by thermometers only the superficial.

Reverting to the diagram (Figure 29), we may regard the air column *A C* as consisting of two parts, of which the lower, *A D*, is controlled in temperature by the contiguous ground and oscillates daily through a wide thermic range, while the upper and greater, *C D*, is influenced only by radiant heat and is relatively constant. The same layer of thermally variable air includes the upper barometric station as well as the lower, so that the thermometer reading at *B* affords no indication of the temperature at *C*, and the temperatures observed at *A* and *B* absolutely fail to give the temperature of the air column *A C*. They therefore fail to afford the data demanded for the computation of the altitude.

The trouble does not end here, although its chief element has been outlined. It would perhaps not be a matter of great difficulty to acquire information about the upper air mass if its relation to the ground layer were simple, but such is never the case. Whenever the ground layer is cooler than the air above, it is of course heavier, and, like any other heavy fluid, it flows down hill and accumulates in valleys, forming lakes of cold air. The nightly layer of abnormally cool air is therefore thinner on eminences than in valleys, and the contrast increases as the night advances. When the conditions are reversed, so that the ground layer is warmer than the air above it, it has a tendency to rise, but accomplishes the change in an irregular manner, breaking through the immediately superior layer here and there and rising in streams, which spread out in sheets wherever the conditions of equilibrium are reached. The conditions of equilibrium are greatly affected by the amount of moisture in the rising streams, and it results that the stratification of the air is notably irregular with regard to temperature. Observers in balloons, as they ascend or descend, rarely find an orderly succession of temperatures. If, therefore, we could in some way determine the temperature of

when from these hourly means separate computations are made of the difference in altitude of the two stations, the results are found too great for certain hours and too small for others. The element of the computation which varies most greatly from hour to hour is the temperature, and the differences in result are therefore ascribed to errors in the determination of the temperature. It is a simple matter to reverse the process and ascertain what temperature at each hour will give a uniform determination of altitude, and this has been done by Plantamour, Rühlmann, and others. The general result of their investigations is that the general temperature of the atmosphere undergoes a daily change which is exceedingly small, amounting in the Alps to only 4° Fahr. in summer, and less than 2° in winter.

some point of the upper hypsometric column, $C\ D$, we should still be unable to deduce the mean temperature of the column with a high degree of accuracy.

DEVICES FOR THE ELIMINATION OF ERRORS DUE TO TEMPERATURE.

At least six different methods have been either employed or recommended for avoiding or eliminating the errors which arise from the imperfection of our means of ascertaining the temperature of the air column weighed by the barometers.

Since the error inheres primarily in the temperatures observed at the two stations whose difference of altitude is to be ascertained, the most obvious way to eradicate it is to apply a correction to the thermometer readings before using them in the computations. Wherever long series of observations of the thermometer and barometer have been made at corresponding stations, high and low, it is practicable, by discussing the means of the series, to ascertain what correction should on the average be made to the thermometer readings at different hours of the day and at different seasons of the year in order to obtain accurate determinations of height; and this work has been performed by various investigators for several different pairs of stations, the results being embodied in tables of corrections.

When these tables come to be applied, however, a high degree of accuracy is not attained, and for this there are two reasons:

In the first place, there is a great dissimilarity in the observed temperature oscillations of consecutive days. The correction which would be appropriate to a certain hour of the average July day, for example, will apply closely to very few individual July days, being too great for some and too small for others. This difficulty has been partially met by constructing two tables, one for clear and the other for cloudy weather.

In the second place, it has been found that each set of tables has a fair degree of usefulness only in a limited district including the locality where the data for its construction were derived, and that it almost uniformly fails when applied to remote districts. The daily and yearly cycles of temperature depend so largely on purely local conditions that the order of change observed in one locality cannot be assumed in advance to obtain in any other.

A second method employed to eliminate the errors is to apply corrections, not to the observed temperatures, but to the computed altitudes. For this purpose also tables have been constructed, and they do not essentially differ from those described above, except that they aim to remove errors arising from the moisture of the air as well as from its temperature. They are open to the same criticisms, for they assume

the similarity of consecutive days and include local peculiarities which prevent their universal application.

A third method is closely allied in principle to the preceding but seeks to avoid the errors instead of eliminating them from the result. It consists in the selection of favorable hours of the day. If we examine any table prepared for the application of either of the preceding methods we shall find that for each month of the year there are certain hours of the day when the indicated corrections are either very small or nothing at all, and it is evident that by selecting those hours for our observations of temperature and pressure we shall obviate at least the use of the tables of correction. The same difficulties, however, inhere in this plan. The critical moments at which the observed temperatures truly represent the conditions of the air column occur upon the average at about the same time of day in the corresponding seasons of each year, but they unfortunately vary so greatly from day to day that it is nearly useless to seek them; and when to this consideration is added that of the inconvenience of making observations at prescribed hours, the method retains little to recommend it. Moreover, the element of locality enters so largely, and in ways apparently so anomalous, that no general rules for the selection of hours are practicable. For example, the tables constructed by Whitney for California indicate that below the altitude of 2,400 feet the most favorable hour for barometric work in January is 6 p. m., while above 2,400 feet noon is preferable.

A fourth manner of procedure ignores altogether the readings of the thermometers at the two stations at the moment of barometric observation, and substitutes therefor the mean temperature for the day, deduced either from a series of observations extending continuously through the twenty-four hours, or else from observations at 7 a. m., 2 p. m., and 9 p. m.,—which have been found by trial to give approximately the same result. It is thus assumed, first, that the temperature of the included air column undergoes no change whatever during the twenty-four hours, and, second, that the daily mean of temperature as deduced from observation truly represents the actual temperature of the air column. Neither of these assumptions can be true; but they approximate so much more nearly to the truth than does the alternative assumption that the desired temperature of the air column is represented by the thermometric readings at the moment of barometric observation, that a great advantage follows their substitution. The error of the first assumption is not great, but it is certainly appreciable and should not be neglected if it is possible to apply a correction. Plantamour's discussion of the great series of Swiss observations shows that the temperature of the main body of the atmosphere is there in midsummer 4° Fahr. higher in the afternoon than it is at early morning, and such a difference of temperature, when converted into altitude, amounts to eight feet in each thousand.

We have at present no means of knowing that the conclusions de-

rived from the Swiss observations are entitled to universal application, but it is reasonable to expect that future investigation will enable the construction of tables whereby an approximately true diurnal sequence of temperatures can be substituted for the assumed diurnal uniformity of temperature.

The second assumption, that the daily mean temperature of the air column is equal to the half sum of the daily mean temperatures of the two stations as determined by continuous observations, is probably true when averages of long periods are considered, but is fallacious as applied to individual days. And there is little ground to hope that future investigation will discover any method of correcting the errors involved in the means of individual days as derived from observation.

The fifth method is one of avoidance rather than correction. It consists in having the base station at approximately the same altitude as the new station, so that the included air column is of small height and the error dependent on the inaccurate determination of its temperature inconsiderable. This method is highly efficacious, but the opportunities for its application are rare. It was successfully employed, however, by the survey in charge of Dr. Hayden for the measurement of the numerous high peaks of Colorado. A base station was established on one of the peaks and to it were referred all new stations of similar altitude.

A sixth method was proposed by Rühlmann, but has perhaps not yet been put in practice. His plan consists essentially in deducing the temperature of the air from barometric observations made at points of known altitude simultaneously with the observations at the stations whose difference it is desired to ascertain; the temperature thus obtained is then used in the computation of the desired altitude. The advantages of this method are believed to be great, but since it is closely allied in principle to the method it is the purpose of this paper to present, and will have to be discussed at length in a succeeding chapter, its consideration is deferred for the present.

HUMIDITY.

The errors which depend upon the humidity of the atmosphere resemble those due to temperature in that they arise from the imperfection of our means of ascertaining the actual condition of the air column. It is a common practice to make instrumental tests of the amount of moisture contained in the air at hypsometric stations, but there is reason to believe that these tests convey very little information as to the actual condition of the air column concerning which knowledge is desired. The error thus accruing is less than in the case of temperature, only because humidity is a much smaller factor of the hypsometric problem.

The variability of the distribution of moisture in the atmosphere

arises from the atmospheric circulation, taken in conjunction with the laws of condensation. Aqueous vapor is diffused so slowly in air, and its relative amount in the atmosphere is so small, that its movements are not independent, and it is practically carried by the air. Whenever, therefore, a current of air moves upward and its temperature is lowered by rarefaction, a point may be reached where the accompanying vapor can no longer exist as such and is condensed to cloud or even to rain or snow.

Whenever a current of air moves downward, on the other hand, its capacity for moisture is increased, and it acquires a *quasi*-absorbent power so as to take up water from whatever moist surface it touches. At the surface of the earth there is an almost continuous passage of moisture from ground to air, only a part of the total exhalation being returned as dew. The daily circulation incited by the heat of the sun carries the moistened air upward, and eventually the water is returned to the earth in the form of rain. The acquisition of moisture by the air is greater by day than by night, and the precipitation is exceedingly irregular, so that in the distribution of the moisture there is a tendency toward heterogeneity, which is only imperfectly met by the slow process of molecular diffusion. Probably the most variable stratum of all is that next the earth, and it is to this that psychrometric observations are almost invariably confined. A change of station of a few feet, or a slight variation in the direction or force of the wind, will often cause a very important difference in the indications.

Similar irregularities are observed by aeronauts, who rarely if ever obtain humidity records indicating an orderly diminution from the ground upward, and the irregularities which they observe are more striking than the associated irregularities of temperature.

It is therefore generally conceded that the moisture observations which the hypsometer is able to make are of little service to him, unless it be in the form of means derived from long series.

DEVICES FOR THE ELIMINATION OF ERRORS DUE TO HUMIDITY.

Several of the devices employed to obviate errors of gradient and errors of temperature include at the same time errors of humidity, and it will be unnecessary to repeat their description here. The following methods apply to the moisture element only.

First. It is a common practice to ignore the changes announced by the psychrometers from hour to hour, and from day to day, and to use instead of individual readings the mean of observations for a considerable period of time, such as a week or a month.

Second. It is also a common practice to ignore altogether the indicated changes of moisture, and assume that the influence of moisture upon the density of the atmosphere is strictly proportional to that of temperature. This is done by ascribing to the temperature an effect

slightly greater than that due to the expansion of the air and omitting altogether the moisture term of the hypsometric formula.

This practice finds a certain warrant in the general fact that warm air can hold, and on the average does hold, more moisture than cold, but it is to be doubted whether the results thus obtained are as accurate as those by the first method. It is not easy to test the matter, for the errors due to temperature, while they are to a certain extent analogous to those arising from humidity, are so much greater in amount that they mask them and render their discussion a matter of difficulty. There can be no doubt that either of these methods is preferable to that which employs a single psychrometric observation made in conjunction with the reading of the barometer as an indication of the coincident condition of the atmosphere; either of them is sufficiently accurate for the present, or until the more serious difficulties arising from gradient and temperature are more successfully met than they have been hitherto.

ERRORS OF OBSERVATION.

It has been assumed in the preceding pages that the instruments employed faithfully record the condition of the atmosphere in which they are immersed, that they are not exposed to abnormal local conditions, and that they are accurately read. As a matter of fact, however, meteorological instruments are neither perfect in their construction nor capable of giving trustworthy indications unless handled with skill and care, while it is a matter of the utmost difficulty to secure strictly normal local conditions. We will give brief consideration to the principal errors of observation, and to the precautions which are found to diminish them.

Take, first, the thermometer which is used to measure the temperature of the air. The mercury in the bulb exchanges heat with the surrounding air by conduction, and would acquire precisely the temperature of the air if cut off from the influence of all other sources of heat. There is, however, a constant interchange of heat between all bodies, including the thermometer, by radiation, and if the surfaces in the vicinity of the thermometer have a different temperature from it, they influence its temperature. Even the body of the observer communicates an appreciable thermic effect to the thermometer before him. It is important, therefore, that the thermometer be insulated from all bodies which have not the temperature of the air; but this must be accomplished without depriving the air itself of free access to the bulb. At fixed observatories insulation is usually attained by surrounding the thermometer stand by a wooden lattice, but when observations are made out of doors by itinerary topographic parties the most that is ordinarily done is to place the thermometer in the shade and in such position that it receives radiation from no greatly heated object nor brilliant reflector. The influence of the body of the observer is avoided by approaching the

thermometer only when the moment has arrived for reading it, and then making the observation as quickly as possible, before the communication of heat has been great enough to acquire importance.

The psychrometer in ordinary use consists of a pair of thermometers, one of which is exposed to the air in the usual manner, while the other is exposed with a moistened bulb. The evaporation of moisture from the surface of the wetted bulb has a cooling effect, and causes that thermometer to indicate a lower temperature than the other. The difference between the readings of the two thermometers enables the humidity of the air to be computed. Observations with this instrument evidently suffer from all the defects of exposure which affect the measurement of the temperature, and they incur, moreover, some special difficulties, which need not be described because they are overshadowed by that arising from the inequality of the distribution of moisture in the air. Except in very moist weather the heterogeneity of the air near the ground is so great that the aqueous contents indicated by the psychrometer at any instant are, within wide limits, a matter of accident. The best that can be done by the observer is to avoid making his measurement on the lee side of a surface affording rapid evaporation.

The barometer, like the thermometer, is subject to errors caused by radiant heat, but in a somewhat different manner. The mercury of the barometric column, and the scale (usually of brass) by which its height is measured, expand in different degree for the same addition of heat, and it is necessary to know their temperatures in order to make proper allowance. The temperature of the instrument cannot be accurately measured unless it is uniform throughout, and unequal radiation from different sides interferes with this uniformity.

The barometer therefore is not merely hung in the shade so as to avoid the direct rays of the sun, but is insulated as far as practicable from all sources of radiant heat, and is not approached by the observer until the moment for observation has arrived.

The brass scale is usually so thin that it undergoes changes of temperature more rapidly than the mercury. If, therefore, the temperature of the surrounding air be gradually raised, the brass scale responds more promptly than the mercurial column and becomes relatively too long, while the reverse takes place if the temperature is lowered. It results that a rising temperature gives too low an estimate of barometric pressure, and a falling temperature too high. If the change is rapid, the record may be vitiated to the extent of ten or fifteen thousandths of an inch. The precaution generally recommended is to put the barometer in position and leave it with unchanged conditions for fifteen or twenty minutes before observation.

In portable barometers of the pattern in ordinary use in this country the tube containing the mercury is of so small caliber that the movements of the mercury are influenced by capillarity. The mercury is prevented from standing as high as it otherwise would, and its rise and

fall are impeded. The errors thus occasioned have been corrected in various ways. They can be avoided altogether by giving to the tube a large bore, but the portability of the instrument is thus destroyed. Tables of corrections have been prepared, but their application is rendered difficult by the inequality of bore, not only of different tubes, but of different parts of the same tube. The greater part of the difficulty from sluggishness, but not the whole, is removed by jarring the tube immediately before the reading is taken, so as violently to overcome the *quasi* adhesion of the surface of the mercury to its sides. The only known practicable method of making due allowance for the individual peculiarities of each barometer is to compare it with a standard under all conditions of pressure, and record its errors, basing upon them afterwards a table of corrections.

A third occasion of false estimate of pressure, and the most insidious of all, is found in the influence of wind. If during a strong wind the room in which a barometer is placed have apertures on the windward side open, and all those on the opposite side closed, an abnormal quantity of air is forced into it, increasing its atmospheric tension and causing the barometer to rise. If, on the other hand, the windward apertures are closed and the leeward opened, a suction is produced whereby the quantity and tension of air in the room are abnormally diminished and the barometer is made to fall. Every aperture in every room contributes in some way to the influence of the wind upon the atmospheric pressure in the room, and this influence varies constantly, not only with the force of the wind, but with its direction. If the barometer be hung out of doors the wind does not lose its influence but merely changes the point of application. The cistern of the barometer is itself a room, communicating by an aperture or apertures with the external air, and is as truly subject to abnormal tension as a larger inclosure.

The errors which may thus arise in the case of strong winds are large, amounting in some instances to the 180th part of the atmospheric pressure,* and affecting the determinations of altitudes by more than one hundred feet. Recent investigations encourage the hope that the pneumatic principles upon which these abnormal tensions depend will soon be so well known that it will be possible either to avoid or to correct the errors they occasion, but for the present the only known method of escape is by choosing for observation periods of calm or of light wind.

GENERAL DEVICES FOR DIMINISHING HYPSOMETRIC ERRORS.

There are a number of the devices mentioned above under the several heads of gradient, temperature, and humidity, which in their appli-

* See Chapter IV for demonstration of the influence of the wind on the barometer observed on the summit of Mount Washington.

cation always have the effect of diminishing errors of more than one class; and there are, moreover, certain general methods of procedure, when many stations are to be treated together, which conduce at the same time to accuracy of result and economy of effort. These will now be taken up in order.

I. The chief of the general devices which have already been mentioned, is that of the empiric correction to the computed altitude. When the difference of altitude of two stations is computed repeatedly from a large number of observations, covering all parts of the year and all hours of the day, it is found that the results obtained at some seasons are on the average larger than those obtained at other seasons, and that those reached at certain hours of the day are on the average larger than those reached at certain other hours. From such series of results it is a simple matter to deduce corrections which, being added to the individual results, will make them accord better with each other and with the actual difference of altitude. Such tables of corrections have been prepared in India, in California, and in Europe. To be of value they must be based upon the means of long series of observations; and all of the best of them are so based. As a rule, they contain a correction for each month of the year and each hour of the day, and are therefore adapted to the elimination of all errors, from whatever source, which have either a yearly or a daily period. They include the errors dependent on annual gradient, on diurnal gradient, and on the annual and diurnal variations of temperature and moisture. The influence of non-periodic gradient escapes them, and so does the influence of all non-periodic variations of temperature and humidity; and with the latter is included a very important factor—the non-periodic variation of the amplitude of the diurnal oscillation of temperature. Nevertheless, the elimination of periodic errors is a matter of so great importance that the device would be eminently useful were it not for the local restriction to its application.

Such a table of corrections, when applied to the identical pair of stations at which were made the observations on which it is based, gives good results; applied to another pair of stations in the same neighborhood it affords results somewhat less accurate; and applied to stations at a distance it fails altogether to enhance the accuracy of the determinations. It is therefore not universal in its application, but strictly local, and, in order to give the device a general application, special tables of correction need to be deduced for every district in which it is desired to apply them.

It might at first seem natural that a system of errors dependent upon the periodicity of the supply of solar heat would be identical the world over and might be eliminated by a single system of corrections, but as a matter of fact they cannot be so eliminated, and the difficulties which stand in the way are not far to seek. While the sun is the prime cause of all atmospheric perturbations, and while the variations in the amount of solar heat which reaches any given spot are charac-

terized by the most definite diurnal and annual periods, its influence is nevertheless greatly modified by conditions, and some of these conditions are purely local. The principal ones are as follows:

First. *Latitude.* If this were the only one it could be readily taken account of, and it would be a simple matter to compute empiric corrections for all latitudes.

Second. *Relation to ocean currents.* The circulation of the ocean causes the transfer of great bodies of warm water toward the poles, and of bodies of cold water toward the equator, and these moving bodies of water, having each a temperature differing from the mean temperature of the adjacent land, become themselves, so far as meteorologic problems are concerned, actual sources of heat and cold, and give to special localities which fall within their influence hypsometric conditions entirely independent of latitude.

Third. *Forms of land surface.* The reliefs of the earth, by modifying the direction of winds, by localizing precipitation, and in numerous other direct and indirect ways, have an influence upon the condition of the atmosphere, which is none the less actual because in the present state of meteorologic science it is difficult to formulate.

Fourth. *Textures of land surface.* The highly different powers of absorption and radiation possessed by surfaces of earth of various colors, by verdure, by naked rock, by snow, and by water, affect greatly the diurnal and even the annual variations of temperature, moisture, and gradient; and their influence is of a complex character that defies close analysis. The hypsometric periodicity of a locality is therefore controlled by the physical characteristics of its vicinity—by its environment, that is,—just as perfectly as is its weather, and we can hardly look forward to the time when meteorology will be so far enabled to analyze and weigh these various influences as to render it possible to adapt a system of empirical barometric corrections to all times and all places.

The hypsometric device which applies an empiric correction to the observed temperature of the air is practically identical with that which applies a correction to the computed altitude, for although the adjustment of the temperature is primarily for the purpose of correcting the periodic errors introduced by a false estimate of the thermic condition of the air, it is always deduced in such way as to correct at the same time all other errors having the same period. It is, therefore, subject to the same limitations in its application as the preceding device, and the same remarks apply to it.

The method which depends upon the selection of hours of observation relies also on the same principle, and has the same advantages and disadvantages.

The hypsometric method which substitutes series of observations for individual observations is ordinarily barred from use by its expense, but there are occasional circumstances which render it available. It

is especially useful in determining the altitudes of meteorologic stations which are permanently occupied for other purposes. When the series of observations at each station is hourly and extends through an entire day, it serves to eliminate, either approximately or completely, all errors which exhibit a daily period. These are the diurnal gradient, the diurnal temperature error (which is the chief error arising from the temperature of the air), and the diurnal moisture error. The non-periodic and annual gradients are practically unaffected, and it is probable that there is usually a large residual inaccuracy in the determination of humidity.

If the series of observations be extended through so long a period as a month, errors dependent upon humidity are greatly reduced, and if they have no large local factor, such as that which arises from the proximity of a surface of rapid evaporation, they are practically canceled. The influence of non-periodic gradient is greatly diminished also, for usually in such a period of time it shifts its direction several times and approximately neutralizes itself in the mean result. If the series of observations embrace an entire year, the effect of annual gradient also disappears, and, theoretically, nothing remains but the perennial gradient. It is found, however, in practice that there is a small residual inequality.

The method which depends upon the establishment of numerous base stations in a vertical series is likewise highly efficacious, and might be widely employed but for its expense. It affords no relief to the troubles imposed by annual and non-periodic gradients, and it is a matter of doubt whether it greatly diminishes the influence of diurnal gradient, but it practically excludes all errors arising from our imperfect knowledge of the temperature and humidity of the air. Those errors are proportioned, *cæteris paribus*, to the difference of altitude between the new and base stations, and if the base station is in every case selected so that this difference of altitude is small, the errors are thereby rendered insignificant.

II. We now turn to the second class of general methods. Nearly everything that has been said in the preceding pages applies to the case in which it is desired to ascertain the height of a single station, but in by far the largest part of hypsometric work a great number of new stations, lying more or less in the same neighborhood, are visited in rapid succession, and are all referred to the same base station, where a continuous series of observations is maintained. This is the case wherever the barometer is employed to furnish the vertical data for a map of a mountainous region, and it is under such conditions that the barometer as a hypsometric instrument is chiefly employed.

When the scheme of stations consists of a base station where observations are made at short intervals for a long period, and numerous new

stations at each of which the barometer is read either once only or at most a few times, temperature and moisture observations can be made of better quality at the base station than at the others. Such a base station is, or should be, provided with means for protecting its thermometers from all sources of radiant heat much better than is possible during the hurried observations of an itinerary party; and the uniformity of the local conditions by which it is surrounded tends to give a uniformity or harmony to the hypsometric results, which for most purposes is desirable even though constant errors are involved. It is usually more important that determinations of altitude within the field of a map be consistent with each other than that they be absolutely correct. For this reason some geographers have preferred to confine their observations of temperature and moisture to the base station and carry no instruments but barometers to the new stations. For purposes of computation, the temperatures of the new stations are deduced from those of the base by adding or subtracting a number of degrees corresponding to the difference of altitude, allowing a certain fraction of a degree for each unit of vertical distance; and a similar empiric rule is applied to the moistures. It is an advantage of this method that it admits of the substitution of the mean air temperature for the twenty-four hours in place of the temperature observed at the hour of barometric measurement, without prolonging the observations at the itinerary or new station into a daily series. It also admits of the derivation of a vapor correction from the mean of observations extending over a considerable period of time. There can be little question that it is superior both in economy and accuracy to the system which sends the thermometer and psychrometer along with the itinerary barometer and afterward employs their indications in the computation of altitudes.

Advantage is frequently gained, also, by the employment of intermediate stations, or temporary base stations. It often happens in the conduct of surveys that a field party retains its headquarters for several days in one place, during which time one or more barometric stations are made near by, and it is considered desirable in such case to carry on a series of barometric observations at the headquarters during the whole of the time. By means of these it becomes possible to determine the altitude of the headquarters station more accurately than could be done if a single observation only had been made, and if its situation is at some distance from the barometric base station it is better in the computation to refer the itinerary stations of the vicinity to it than to the principal base station. The principal error obviated by this means is that due to non-periodic gradient.

Another general method consists in the combination of barometric determinations with trigonometric. In any survey which is based upon triangulation the points occupied by the map-makers are necessarily intervisible, so that, if their distances are not great, it is possible to

ascertain their relative altitudes by means of vertical angles, and this with a degree of accuracy to which the barometer has not yet attained. If, as is usually the case, the stations occupied by the topographer are also "new stations" of the barometric scheme, great accuracy can be attained by the combination of the two classes of data. The relative altitudes determined by means of vertical angles enable the computer to refer all the barometric determinations of altitude to a single point and there combine them. The mean result given by the combination has far higher claims to accuracy than any single determination, and affords a trustworthy initial point for the system of relative altitudes measured by the topographer. All classes of barometric errors are by this method diminished, and the altitude determination for each station of the entire system acquires an accuracy comparable with that which would be given by a continuous series of observations at a single new station extending through the whole period of field work.

RELATIVE IMPORTANCE OF DIFFERENT SOURCES OF ERROR.

In the preceding enumeration of the sources of error which affect the use of the barometer little has been said of their relative importance. It is indeed impossible to compare them in a strict way, because they are conditioned by different circumstances. The errors arising from non-periodic gradients are approximately proportional to the force of the wind and to the horizontal distance between the base and new stations. Those which arise from diurnal gradient are apt to be greater when the difference of altitude is great. Errors arising from temperature and moisture are proportional to the difference of altitude, but are influenced also by the time of day, the season of year, and the relation of the stations to the ocean. The errors, therefore, which affect the determination of the height of a mountain above its base are those of temperature, moisture, and diurnal gradient, while the difficulty encountered in determining the relative altitude of two stations upon a plain arises almost entirely from non-periodic gradient.

It will be instructive, however, to assume a case as representing the average of conditions under which barometric hypsometry is ordinarily conducted and show in what proportion the result is likely to be affected by the various factors. We will assume that one station is five thousand feet higher than the other, that they are fifty miles apart, and that they are situated in the temperate zone, remote from the ocean. We will assume further that the observations, a single pair, are made near the middle of a clear day in summer, and that a light wind is blowing at the time. The following table presents in its first column of figures the probable error in feet arising from each of the indicated sources, and

in its second column the possible error,—all of the errors being estimated by the writer from the consideration of actual cases.

	Probable Error, in feet.	Possible Error, in feet.
From annual gradient	6	20
From diurnal gradient	8	30
From non-periodic gradient	20	50
From temperature	100	300
From moisture	10	20
From imperfection of observation	10	No limit.
Totals	103*	420

The conspicuous feature of the table is that the temperature error is not only the greatest under ordinary circumstances, but that it exceeds the total of the others, so that it is with good reason that hypsometric students have given their chief attention to devices for avoiding or correcting it. That from non-periodic gradient stands next, and it may fairly be said that if these two are neglected it is a waste of time to provide against the others. It must be remembered, however, that these errors are estimated on the assumption that none of the special devices recited in the preceding pages are employed, save only the universal device of the base station. As a matter of fact very little work is now carried on without recourse to some of them, and it is probable that the average error of the determinations of altitude which have been made during the past decade is less by one-half than the table would imply.

THE PRACTICAL PROBLEM.

The difficulties which inhere in the use of the barometer for the measurement of heights are so numerous and so baffling that there is no reason to hope they will ever be fully overcome. The best that can be done is to mitigate them, and the real question to be answered is, What efficiency is it practicable to give to the barometer? The question is largely an economic one, for it is always possible to obtain by means of the engineer's level a degree of precision absolutely impossible to the barometer, and it can therefore never be profitable to employ a barometric method so elaborate that its cost will approach that of the use of the spirit level. Moreover, in that important branch of hypsometric work in which many points are to be determined within a limited district, the engineer's transit and allied instruments for the measurement of angles

* When a measurement is subject to errors from two or more sources, its *probable error* (using the term in its mathematical sense) is equal to the square root of the sum of the squares of the probable errors from the several sources.

are able to do the work much cheaper than the engineer's level, and their degree of precision is in general higher than that of the barometer. In such cases the barometer must therefore be handled with still greater regard to economy if it is to retain its place in the field.

It has been practically demonstrated that in the work of mountain surveys protracted series of observations can economically be made at base stations, and it is almost equally certain that the protracted occupation of new stations, even for a single day, is economically inadmissible. The problem therefore which occupies the attention of those who have occasion to use the barometer in extended surveys is how to secure the best result from a single observation at a new station, combined with series of observations at one or more base stations.

The preceding pages have described all the principal methods of procedure that have been employed in the past; the following will set forth the new method which forms the theme of this paper.

CHAPTER II.

THE NEW SOLUTION.

In the following pages a new system of barometric hypsometry is presented.* It is not of universal application, but the range of work to which it is adapted is large, and it is believed that such tests as have been applied give it sufficient indorsement to entitle it to the attention of the geographer.

The new system proposes a new method of observation and a new method of computation.

The *method of observation* is as follows: Two base stations are established—one high, the other low. Their difference in altitude is made as great as practicable, and their horizontal distance is made as small as practicable. Each is furnished with a barometer, and a barometer only, and observations are made at frequent intervals through each day, as in the ordinary system. At each new station a barometer is observed, and no other instrument,—the psychrometer and all thermometers, except that attached to the barometer, being discarded. The difference in altitude of the two base stations is determined by spirit level and constitutes a vertical base line by which all altitudes are gauged.

The field-notes thus consist of three series of barometric readings, pertaining respectively to the upper base station, the lower base station, and the new stations.

The *method of computation* is as follows: The readings are first corrected for index error and temperature of instrument. They are then collected in groups of three, each observation at a new station being associated with the coincident observations at the two base stations. The altitude of the upper base station above the lower is now computed in the usual manner, except that no corrections for moisture, temperature, or gravity are applied—that is to say, it is computed on the assumption that the air is dry and has a uniform temperature of 32° F.; and the same computation is made of the altitude of the new station above the lower base. The results of these computations will

* The first publication of the system was made in a communication to the Philosophical Society of Washington, in 1877. (See page 131 of the Bulletin for that year.)

be called the approximate height of the base line and the approximate height of the new station.

The following proportion is then made—

$$\left\{\begin{matrix}\text{The approximate}\\ \text{height of the}\\ \text{base line } (\mathit{B})\end{matrix}\right\} : \left\{\begin{matrix}\text{The true height}\\ \text{of the base}\\ \text{line (B)}\end{matrix}\right\} :: \left\{\begin{matrix}\text{The approximate}\\ \text{height of the}\\ \text{new station } (\mathit{A})\end{matrix}\right\} : \left\{\begin{matrix}\text{The true height}\\ \text{of the new sta-}\\ \text{tion (A)}\end{matrix}\right\}$$

whence

$$\frac{\mathit{B}}{\mathrm{B}}=\frac{\mathit{A}}{\mathrm{A}} \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \quad (1)$$

Here all the terms are known except the true altitude of the new station (A) and that is deduced by the solution of the equation. This is the essential nature of the computation. As will be presently explained, its form is changed as a matter of convenience, and a small correction is added.

The theoretic basis of this procedure will now be given. The weight (W) of the air column included between the upper and lower bases is determined by the barometers for the instant of observation. It is equal to the product of the mean density (d) of the column, multiplied by its height (B), multiplied by a constant factor (E)*.

$$\mathrm{W}=\mathrm{d\,B\,E} \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ . \quad (2)$$

B is the approximate height of the same column, computed on the assumption that its mean density is that which would obtain if it were free from aqueous vapor and had a uniform temperature of 32° F. Calling this assumed standard density d, we have

$$\mathrm{W}=\mathit{d\,B}\,\mathrm{E} \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ . \quad (3)$$

Dividing this last equation by the preceding, member by member, we obtain

$$1=\frac{\mathit{d\,B}}{\mathrm{d\,B}} \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \quad (4)$$

whence

$$\frac{\mathit{B}}{\mathrm{B}}=\frac{\mathrm{d}}{\mathit{d}} \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \quad (5)$$

The ratio of the approximate height of the base line to its true height is thus found to equal the ratio of the actual density to the assumed or standard density; and it is the measure, therefore, of the temporary condition of the column with respect to density.

Evidently an identical process of reasoning will show that the ratio of the approximate height of the new station to its true height is the

* The composition of this factor is omitted from the text because it is not essential to the discussion. It includes the area of the cross-section of the air column and the weight of a unit volume of dry air at a standard temperature of 0° Cent., and under the standard pressure of 760^{mm}.

measure of the temporary condition, with respect to density, of the air column included between the new station and the lower base station.

Equation (1) postulates that the temporary condition of one air column is identical with the simultaneous condition of the other—with respect to an assumed standard of density. It does not postulate equality of densities, for the assumed standard is not a uniform density, but is that system of densities which would obtain under the logarithmic law in both columns if the air were dry and of a uniform, standard temperature. It merely postulates that the temporary accidents of temperature and moisture affect both columns alike.

What is practically done is to deduce from the comparison of the computed height of the base line with its true height a ratio or coefficient expressive of the temporary local variation of density, and then to apply this coefficient in the simultaneous determination of the height of a partially coincident air column. The first member of Equation (1) deduces the coefficient; the second applies it.

One of the distinctive characteristics of this hypsometric method is that it observes density directly, whereas other methods observe temperature and moisture only and deduce density. The only reason which has ever existed for measuring air temperatures in hypsometric work has been to ascertain the density of the air, and the only reason for measuring the moisture of the air has been to ascertain its density. A second distinctive feature is that the new method employs in its determination of density a column of air comparable in height with the one to be measured and fairly representative of it, while other methods base their diagnosis of the column to be measured on density determinations made close to the ground, where, as a rule, the conditions are not representative. A third is that the process which determines the density is the simple inverse of the process which applies it in the computation of the desired height.

THE FORMULA.

We shall now proceed to develop the full formula for the computation of altitude, considering, first, what may conveniently be called the *logarithmic term*, and, second, what may be called the *thermic term*. The logarithmic term will embody the relation postulated by Equation (1); the thermic term will express a necessary qualification of that postulate.

Let L, U, and N represent the altitudes of the lower base station, the upper base station, and the new station, respectively, and assume $L < N < U$. Let l, u, and n represent the synchronous barometric readings at the same stations, corrected for temperature of instrument and index error.

Let B=the vertical base line, or the difference of altitude of the two base stations. $B=U-L$.

Let A = the required difference of altitude, N−L, and a its uncorrected value as deduced by Equation (1)*. Since B=U−L and A=N−L, B−A=U−N.

All vertical distances are referred to the lower base station as an origin.

The approximate height of the base line, deduced by the logarithmic law (p. 406) from the barometric readings at the two base stations, is—

$$C\,(\log l - \log u),$$

in which C is a constant. The approximate height of the new station above the lower base station is—

$$C\,(\log l - \log n).$$

With the substitution of this notation the proportion on page 438 becomes

$$C\,(\log l - \log u) : B :: C\,(\log l - \log n) : a,$$

whence

$$a = B\frac{\log l - \log n}{\log l - \log u}, \quad \ldots \ldots \quad (6)$$

an expression free from the constant C.

This is the logarithmic term of the formula. It would need no companion if the atmospheric column were uniform in temperature and if its aqueous vapor were uniformly distributed; but since this is never the case there must be added to it a term representative of the influence of the distribution of temperature and vapor on the distribution of densities.

In a general way it is known that the upper layers of the air are cooler than the lower, but the law of variation eludes discovery, being concealed by its multitudinous exceptions. In a general way, too, it is known that the upper layers of air contain a smaller per cent of moisture than the lower, but in this case also the law of variation is obscured by its exceptions. In order, however, to give these elements a place in the formula it is necessary to embody their law of variation, known or postulated, and we shall therefore assume that the collective influence of the two factors upon the distribution of densities in an air column follows a simple arithmetic law, modifying the density of each part of the column by an amount strictly proportioned to its height above the base. Whenever a better assumption becomes possible the term here deduced will need to be replaced by another.

The distribution of densities in the air is determined by three factors: pressure, temperature, and aqueous vapor. They are in reality intimately conjoined, but the considerations about to be adduced will be

* The mathematical reader will observe a change of notation here; a is now used to designate a quantity denoted by A in Equation (1), while A is used for the same quantity plus a correction. In another sense, however, the notation is consistent, for A is continuously used to indicate the quantity sought, the necessity for a correction being ignored until the foundation of the formula had been laid.

rendered clearer by treating them for a moment as independent. If the air were of uniform density at all heights, and the element of weight were introduced alone, the lower strata would be compressed by the weight of those above, and the resulting system of densities would exhibit a diminution from below upward. If the air were of uniform density, and the element of temperature were introduced alone, the high temperatures at low altitudes would cause a dilatation there, the low temperatures at high altitudes would cause a contraction, and the resulting distribution of densities would be characterized by an increase from below upward. If the air were of uniform density, and the element of vapor distribution were introduced alone, the greater per cent of aqueous vapor (which is a rarer gas than dry air) in the lower strata would cause them to be relatively rare, and the resulting distribution of densities would be characterized by an increase from below upward. The pressure factor would make the lower layers of the atmosphere the denser; the temperature and vapor factors would make them the rarer. The pressure factor is by far the most important, and in the actual distribution of densities there is a diminution from below upward; but this upward decrease is a resultant of the upward decrease due to pressure, combined with the upward increase due to temperature and aqueous vapor.

It will be convenient to speak of the factors dependent on temperature and vapor collectively as *thermic*, calling the upward increase of density due to them the *thermic increase* and the density they would by themselves establish the *thermic density;* and it will be convenient to speak of the factor dependent on pressure as *logarithmic*, since its influence is expressed by the logarithmic law. The logarithmic term of our formula gives an approximate altitude for the new station, dependent on the logarithmic factor of density; the thermic term will have the relation of a correction to this.

The mean thermic density of the air column comprised between the new station and the lower base station is by postulate equal to the thermic density of the stratum midway between the two, the altitude of which is $\frac{N+L}{2}$. The mean thermic density of the column comprised between the base stations is in like manner equal to that of the stratum at the height expressed by $\frac{U+L}{2}$. The vertical space between these two midway strata is—

$$\frac{U+L}{2}-\frac{N+L}{2}=\frac{U-N}{2}=\frac{B-A}{2}$$

The difference between the two mean densities will be found by multiplying the number of units contained in this vertical space by the thermic increase of density for each unit of vertical space. The rate of thermic increase being assumed to be uniform from the ground upward,

we may suppose that at some height its total amount becomes equal to the density at the ground, or that when expressed in terms of the initial density it becomes unity. Call that height $\frac{D}{2}$. The thermic increase of density for each unit of vertical space is then expressed by $1 \div \frac{D}{2}$, or $\frac{2}{D}$; and the expression for the difference between the mean thermic densities becomes—

$$\frac{B-A}{2} \times \frac{2}{D} = \frac{B-A}{D}$$

This expression has a linear space for its numerator and another for its denominator, and is itself a ratio. It denotes the fraction by which the thermic increase of density affects the relative densities of the two columns, B and A. Since the heights of the columns are inversely as their densities, the same ratio expresses the fraction by which the deduced altitude, A, is affected by the thermic variation of density. The correction for thermic density is therefore found by multiplying this ratio by A, and is—

$$\frac{A\,(B-A)}{D}$$

Since by postulate $N < U$, the midway stratum of the column A is lower than that of the column B, its temperature is higher, and its thermic density is less. Hence, the neglect of the thermic factor of density in the computation assumes too great a density for A. And since the height varies inversely with the density, the assumption which makes the density too great makes the height too small. The neglect of thermic density therefore gives too small a computed altitude, and the thermic correction should be given a positive sign. The full formula accordingly reads:

$$A = B\,\frac{\log l - \log n}{\log l - \log u} + \frac{A\,(B-A)}{D} \quad . \quad . \quad . \quad . \quad . \quad (7)$$

The assumption that $L < N < U$, or that the new station is intermediate in height between the upper and lower base stations, was adopted for a temporary convenience, but is in reality not essential to the demonstration, and can now be laid aside. When the new station is higher than the upper base, $B-A$ becomes negative and renders the thermic term negative. When the new station falls below the lower base, A becomes negative and renders the thermic term negative. In the latter case, however, $\log n$ becomes at the same time greater than $\log l$, and the logarithmic term is rendered negative; so that, both terms being negative, their numerical combination is by addition.

It was also assumed for simplicity's sake that the altitude of the new station was to be referred to the lower base station. Let us now make the opposite assumption, referring it to the upper base station, and making that station the origin of vertical distances. Calling B′

the base line as referred to the new origin, and A′ the height of the new station referred to the same, we have—

$$B' = -B, \quad \text{and} \quad A' = A - B, \quad . \quad . \quad . \quad . \quad . \quad . \quad (8), (9)$$

whence $$A = A' - B', \quad \text{and} \quad B - A = -A' \quad . \quad . \quad . \quad . \quad (10), (11)$$

Substituting these values in Equation (7) we obtain—

$$A' - B' = -B' \frac{\log l - \log n}{\log l - \log u} + \frac{(A' - B') \times (-A')}{D},$$

whence $$A' = B' \frac{\log u - \log n}{\log u - \log l} + \frac{A'\,(B' - A')}{D} \quad . \quad . \quad . \quad . \quad . \quad (12)$$

This equation is identical in form with Equation (7), but u and l have exchanged places. This is as it should be, because the relations of the upper and lower base stations, severally, to the new station have been reversed. Equations (7) and (12) are indeed special cases of a more general formula. If we designate the barometer reading at that base station used as the origin of distances by o, and the reading at the other base station by s, and call the base line and computed height, as referred to the same station, B_0 and A_0, we may deduce from either equation the following—

$$A_0 = B_0 \frac{\log o - \log n}{\log o - \log s} + \frac{A_0 (B_0 - A_0)}{D} \quad . \quad . \quad . \quad . \quad (13)$$

It is a matter of indifference, so far as the result in absolute altitude is concerned, whether new stations are referred to one base station or the other. As a matter of convenience, however, it is preferable to use the lower; and the remainder of the discussion will be based on Equation (7).

The application of the logarithmic term to the computation of altitudes is simple, and no table is required except a table of logarithms, but the thermic term is not conveniently constituted for direct computation and should be put into the form of a table, with a and B as arguments; a being the briefer designation of the uncorrected altitude, $B \frac{\log l - \log n}{\log l - \log u}$. Such a table is appended to this paper, giving the thermic correction for each 100 feet of a and of B. It will suffice for all general use, but the computer who has a large number of stations referred to a single base line may find it advantageous to construct a special table for the individual value of B, and thus avoid interpolation.

To apply the formula (7) directly without the intervention of a table is inconvenient because the thermic term involves the unknown altitude, A. The following form, which is not strictly identical but approximates closely, is free from this objection—

$$A = B \frac{\log l - \log n}{\log l - \log u} + \frac{a\,(B - a)}{D + a - (B - a)} \quad . \quad . \quad . \quad . \quad (14)$$

It remains to consider the constant D, to which no value has yet been assigned. By definition $\frac{2}{D}$ is the increment of thermic density for an ascent of a unit of space, and $\frac{D}{2}$ is the vertical distance at which the total increment of thermic density amounts to unity. D is therefore a linear space to be counted in feet, or meters, or whatever other unit is used for B and A in the formula. It is also a function of the vertical distribution of heat and moisture in the atmosphere, and since that distribution is a function of the vertical circulation of the air as modified by a great complex of conditions both local and seasonal, it is impracticable to derive D deductively. It can only be ascertained experimentally. Indeed it is only in a mathematical sense that it is a constant; for it is far from being a fixed natural factor, such for example as the coefficient of expansion of dry air. It is rather the average value of a perpetually fluctuating quantity, which we are content to consider in its totality, only because its component elements vary with time and space in a manner too complex for analysis.

Our best means of ascertaining it is to apply our formula to the computation of altitudes already known, and see how large D must be to give the best average result. For this purpose we give Equation (7) the following form,

$$D = \frac{A\,(B - A)}{A - B\dfrac{\log l - \log n}{\log l - \log u}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

and apply it to the barometric observations of stations (in groups of three) whose relative altitudes have been determined by spirit level.

It is important that the stations differ greatly in altitude, each from each, that they be not widely separated horizontally, and that the series of observations include all portions of the year and all parts of the day. At the present time data for a satisfactory determination do not exist, but there are available two series of observations which satisfy some of the conditions.

1. The Geological Survey of California, in charge of Prof. J. D. Whitney, conducted observations for a period of nearly three years at Sacramento, Colfax, and Summit, the barometers being read at 7 a. m., 2 p. m., and 9 p. m. The differences in altitude and the distances of the stations are as follows:

	Distance.	Difference in Altitude.
	Miles.	*Feet.*
Sacramento to Colfax	45	2,399
Colfax to Summit	36	4,590
Sacramento to Summit	77	6,989

Unfortunately the distances are so large that all results derived from the observations are affected by atmospheric gradients; but a certain use can still be made of the annual means.

2. Rühlmann, in his Barometric Hypsometry, gives a table of means of observations made at three stations on the Miesing, citing Bauernfeind as his authority. The series is for a week in August, 1857, and includes the mean for each hour of the day from 8 a. m. to 6 p. m. The altitudes of the stations are:

Station.	In Meters.	In Feet.
Upper	1,883.5	6,179.6
Middle	1,355.6	4,447.6
Lower	815.4	2,675.2

The distances are not given by Rühlmann, and unfortunately the original record from which he quotes is not at this time accessible to me.

The Californian observations embrace the years 1871 and 1872 and portions of the years 1870 and 1873; but for the present purpose, only the series for the two entire years have been employed.

The observations for each year were first divided into two equal parts, the first including the warmer months (May to October) and the second the colder months; and from the means of the barometric observations during each of these periods of six months the constant D was computed by Equation (15). The observations were next grouped according to the hour of day, those at 7 a. m., 2 p. m., and 9 p. m. for each year being considered separately, and the constant was again computed. Finally a separate computation was made from the mean of all the observations.

In the following table the first column of figures gives the several values of D, in feet, and the second the corresponding values of $\frac{2}{D}$, an expression now representing the increment of thermic density for each foot of ascent, and which it will be convenient to call the *coefficient of thermic density.*

The last column contains a comparative expression for the increment of thermic density, derived from the temperatures observed at the highest and lowest stations during the same periods. To obtain it the difference between the temperature means of the two stations was multiplied by Regnault's coefficient of the expansion of gases for each degree of temperature, and the product, which represents the total difference of density at the two stations as dependent on temperature, was divided by the number of feet in the difference of altitude.

TABLE I.

Values of the Thermic Constant, deduced from Californian Observations.

Groups of Observations.	D	$\frac{2}{D}$	Density Increment derived from Observed Temperatures.
Warm half-year, 1871	1,356,085	.00000 148	.00000 379
Warm half-year, 1872	434,204	.00000 461	.00000 462
Mean		.00000 304	.00000 420
Cold half-year, 1871	392,144	.00000 510	.00000 597
Cold half-year, 1872	411,949	.00000 486	.00000 576
Mean		.00000 498	.00000 586
7 a. m., 1871	921,457	.00000 217	.00000 332
7 a. m., 1872	768,417	.00000 260	.00000 451
Mean		.00000 238	.00000 391
2 p. m., 1871	577,118	.00000 347	.00000 527
2 p. m., 1872	365,221	.00000 548	.00000 580
Mean		.00000 447	.00000 553
9 p. m, 1871	476,066	.00000 420	.00000 603
9 p. m., 1872	328,503	.00000 609	.00000 527
Mean		.00000 514	.00000 565
Whole year, 1871	608,361	.00000 329	.00000 488
Whole year, 1872	422,781	.00000 473	.00000 519
Period of two years	497,354	.00000 401	.00000 504

The most striking feature of the table is the variability of the increment. For the year 1872 it was nearly 50 per cent greater than for 1871, and for the warmer half of that year it was three times as great as for the corresponding months of 1871. The cold and warm halves of 1871 gave results strongly contrasted, while for 1872 their results are nearly identical.

A second feature of interest is that the increment of density is greater at 2 p. m. than at 7 a. m., and is greater at 9 p. m. than at 2. This might perhaps have been expected, because the increment is chiefly due to the fact that the heat of the atmosphere is received by its lower layers and passes upward by convection. The resulting gradation of temperature from below upward may be supposed to be heightened during the day while the lower layers are being rapidly heated, and diminished during the night while the lower layers are losing heat.

Analogous considerations would lead us to expect the summer increment of thermic density to be found greater than the winter; but the reverse is true. The mean of two years' observations gives an increment in the warm months only three-fifths as great as in the cold. It is possible that this relation is anomalous, being dependent on the exceptional climate of the great Californian Valley, in which the lower station is situated, but comparative data are wanting.

It is interesting also to note the general correspondence of the two

columns of increments. The right hand column contains values of the upward increment of density due to temperature alone, the values being derived from observed temperatures. The left hand column contains values of the upward increment of density due to temperature and moisture combined, the values being derived from observed pressures. The range of values is smaller in the thermometric series than in the barometric, but nearly all the irregularities of the latter are copied in the former. They agree in giving a larger increment in winter than in summer, at evening than at morning, in 1872 than in 1871.

But while the two series of results show by their parallelism that they have a common basis, they are quantitatively unequal. For each section of the data which was computed separately (with a single exception), the thermometric means give a higher value for the increment than do the barometric, and in the general mean this difference amounts to 12 per cent.

Table II contains the value of the constant and of the density increment computed from the Miesing observations. They are hardly comparable with the Californian results, because they are based on the observations of a single week only, and, in the absence of more precise information in regard to the topographic relations of the stations, it would be hazardous to draw conclusions from them. It is to be noted, however, that they give a decidedly greater value to the increment than do the Californian observations, and they indicate at the same time a greater range of variation dependent on the hour of day.

TABLE II.

Values of the Thermic Constant, computed from Observations on the Miesing in August, 1857.

Hour.	D	$\frac{2}{D}$
8 a. m.	592, 164	.00000 337
9 a. m.	474, 934	.00000 421
10 a. m.	204, 284	.00000 979
11 a. m.	297, 022	.00000 673
12 noon	220, 146	.00000 909
1 p. m.	187, 499	.00001 067
2 p. m.	179, 237	.00001 116
3 p. m.	219, 629	.00000 911
4 p. m.	257, 746	.00000 776
5 p. m.	410, 350	.00000 487
6 p. m.	531, 602	.00000 376
Mean of eleven hours	274, 375	.00000 729

In selecting a value of the constant for incorporation in the formula, the result derived from the Californian series of two years was given a large weight as compared with the result from the Miesing series of one

week, and 490,000 feet (almost identical with the Californian value, 497,354 feet) was adopted. With its substitution the formula (7) reads:

$$A \text{ (in English feet)} = B\frac{\log l - \log n}{\log l - \log u} + \frac{A\,(B - A)}{490000} \quad . \; . \; . \; (16)$$

or

$$A \text{ (in meters)} = B\frac{\log l - \log n}{\log l - \log u} + \frac{A\,(B - A)}{149349} \quad . \; . \; . \; . \; (17)$$

The value cannot be regarded as final, but is merely the best at present attainable. The series of observations on which it is based is far from being the series theoretically most desirable, and its guaranty of accuracy is not unimpeachable. The great horizontal distance by which the stations are separated, and the relative proximity of the lower station to the ocean, expose the result to the influence of gradients both non-periodic and perennial. The limitation of the observations to three hours of the day is another imperfection, for although the means of temperature readings at the three hours approximate closely to daily means, the means of pressure observations do not. Then, too, the leveling by which the altitudes of the stations were measured was conducted merely for the purposes of the railroad engineer and has presumably only the accuracy needed for such work, while the barometric observers at the upper stations were the station-agents of a railroad—men previously unaccustomed to such duties. Professor Whitney notes moreover that there were several breaks in the continuity of the observations, each comprising a number of days, which he filled by interpolation.

The formula here deduced (16 or 17) takes account of the logarithmic law of density, and of the variations of density dependent on the temperature and humidity of the air. In the formulas of Laplace and Bessel there are additional terms which afford corrections to the computed altitude by taking account of certain variations in the force of gravity.

The force of gravity varies with the latitude, and with the altitude of the station, and this variation affects the hypsometric problem in a variety of ways. First, it causes equal masses of air at different places to have unequal weights. Second, it causes equal masses of air at different heights in the same vertical column to have unequal weights; so that their pressures on the air beneath them produce a system of densities not strictly conformable to the logarithmic law. Third, it causes equal masses of mercury to have unequal weights at different places, so that the indications of mercurial barometers are subject to local corrections.

These variations are by no means inconsiderable. In Guyot's computation of the height of Mount Washington above its base, an allowance for them modifies the result by 16 feet; and in the computation of the height of Pike's Peak above its base, their influence amounts to twice as much. Careful consideration was therefore given to them in the con-

struction of the new formula, and it was not without reason that a corrective term was omitted. The warrant for ignoring them lies in the fact that they affect the air column to be measured and the standard air column (base line) to which it is referred, in nearly equal degrees, so that their influence is approximately eliminated by the use of the standard column in the computation. In the logarithmic term of the formula the numerator of the fraction is an approximate measure of the height of the new station above the lower base—involving the local effect of the variation in the force of gravity. The denominator is an approximate measure of the height of the base line—likewise involving the local effect of the variation. The division of one measure by the other eliminates so much of the influence of the variation as is proportional to the heights, and in so doing eliminates nearly the whole of it.

The share that is not eliminated has been computed for a few special cases and found to be so small that it may be disregarded without appreciable error. For all ordinary determinations of altitude it amounts to less than one-fourth of a foot, and it will in no practical computation attain the magnitude of two feet. It is always less than the 100th part of the thermic correction, it never equals the 2,000th part of the computed altitude, and it falls far below the ordinary error of instrumentation.

EXAMPLE OF COMPUTATION.

In August, 1872, the mean pressure at Sacramento was 29.879 inches; at Colfax, 27.475 inches; and at Summit, 23.336 inches.

The altitude of Summit above Sacramento is 6,989 feet. Required the altitude of Colfax above Sacramento.

$\log l = \log 29.879 =$	1.47537
$\log n = \log 27.475 =$	1.43894
$\log u = \log 23.336 =$	1.36803
$\log l - \log n =$	0.03643
$\log l - \log u =$	0.10734
$\log 0.03643 =$	$-$ 2.56146
$\log 0.10734 =$	$-$ 1.03076
Difference $=$	$-$ 1.53070
$\log B = \log 6989 =$	3.84441
Sum ($\log a$) $=$	3.37511
$a =$	2,372.0 feet.
Going to the table with the arguments:	
$B = 7{,}000$ and $a = 2{,}300$, we obtain	+ 22.2
Interpolation for 7,000 $-$ 6,989 $=$	$-$ 0.1
Interpolation for 2,372 $-$ 2,300 $=$	+ 0.3
Total correction,	+ 22.4
Required difference of altitude,	2,394.4 feet.

In practice nothing is written except the column of figures at the right.

When the data are given in inches and thousandths no higher accuracy is attained by using logarithms of more than five places. The value of a has an uncertainty in its tenths, and sometimes in its units, and this uncertainty affects the final result. It is a function of the limit to precision of instrumentation and cannot be avoided by any refinement of computation. So long as our instruments record no pressure changes smaller than the thousandth part of the barometric inch, we only delude ourselves if we consider less than an entire foot in the result. The tenths of a foot are given in the table only as an aid to the accurate determination of the units. After the completion of the computation the tenths are dropped.*

It may be well to direct attention to the fact that the formula (7, 13, or 14) does not require all its quantities to be expressed in terms of the same unit. There must be a common unit for the barometer readings, l, u, and n, and a common unit for B and D; but the algebraic relations permit these two units to differ from each other. The computed altitude, A, will be in terms of the unit employed to express B and D.

*In some of the serial results tabulated in the following pages, the tenths of feet are retained for the sake of their influence on the final mean.

CHAPTER III.

COMPARATIVE TESTS.

The fact developed in the last section—that the constant of the formula is not a constant of nature, but varies from season to season, and even from hour to hour, as well as from place to place—and the uncertainty which attaches to the quantity adopted as the expression of its average value, may appear to condemn the new method of hypsometry in advance. In reality, however, they do not constitute a serious objection; for, in the first place, the uncertainty attaching to the constant affects only a correction which in practice is usually small; and, in the second place, the natural phenomena of which the uncertainty of the constant is an expression, are so intimately associated with the natural phenomenon which renders possible the barometric measurement of heights, that no known barometric method escapes their influence. It is on their account and on account of the impossibility of completely eliminating the errors of gradient from the problem that the determination of heights by means of the barometer must always be a matter of approximation only and never of precision. The question to be asked about the new method is not whether its application will afford an accurate result, but whether it furnishes a closer approximation than other methods without undue enhancement of expense. As compared with what may be called the ordinary method, the system here proposed involves the outlay necessary to establish and maintain two base stations instead of one, and unless it can show an advantage in accuracy of result it can have no claim to adoption. An attempt has therefore been made to compare it with the best methods in use by making parallel series of computations from the same records of observations.

The comparison has been necessarily restricted to localities where continuous observations were made at two stations differing considerably in altitude, which could be regarded as bases; and it has been still further controlled by the desire of the writer to contrast computations made by the new method, not merely with other computations made by himself, but so far as practicable with those made by the advocates of other systems. Three series of observations and computations have been found to answer the conditions; the first by Williamson, the second by Whitney, the third by Plantamour; and these will be discussed in the order named.

COMPARISON WITH WILLIAMSON'S METHOD.

In 1868 Colonel R. S. Williamson published, under the auspices of the Corps of Engineers, United States Army, a treatise* on the use of the barometer for hypsometric purposes, which has served as a guide for nearly all the hypsometric work that has since been conducted in the United States and still holds place in the front rank of barometric manuals. The method of procedure there set forth is especially adapted to reconnaissances and surveys, and, briefly stated, is as follows:

A single base station is used, at which the barometer, thermometer, and psychrometer are observed at stated hours each day. Itinerary observers visiting the new stations employ the same instruments, and take pains to have each of their observations correspond in time with one of the observations at the base station. Series of hourly observations are made for a number of days in each month at the base station and as frequently as practicable at semi-permanent camps of the field parties, the object being to ascertain the nature of the diurnal curves of pressure and temperature both at the base station and in various portions of the field of survey. In the reduction of the results the first step after the application of instrumental corrections is to apply what is called a "horary correction" to each of the barometric readings. This correction is derived from the diurnal curves of pressure, and theoretically eliminates diurnal gradient. The corrected barometer readings for the base station are then plotted upon ruled paper so as to exhibit their curve, and all readings shown by inspection to be influenced by abrupt and violent atmospheric disturbances, such as thunder storms, are discarded, their places being filled by interpolation. The computation of altitude is then made by Plantamour's formula, which takes account of both the temperature and the moisture of the air at the base and new stations. Instead, however, of employing the temperature recorded by the thermometers at the hour of barometric measurement, the mean temperature for the day is used, being deduced from observations at 7 a. m. and 2 and 9 p. m.; and instead of employing the psychrometer readings for the hour of barometric observation, the mean of the psychrometric determinations for a week or month is substituted.

In the year 1878 Colonel Williamson published the results of a series of comparative computations, in which his hypsometric method was contrasted with that of Professor Whitney,† and as a portion of these results were derived from stations to which the new method is applicable they were selected as the basis for a new comparison. In

* No. 15, Professional Papers of the Corps of Engineers, U. S. A. On the Use of the Barometer on Surveys and Reconnaissances. By Major R. S. Williamson. New York, 1868.

† On the Use of the Barometer—being a Compendium without plates of No. 15, Professional Papers of the Corps of Engineers. By Lieut. Col. R. S. Williamson. Washington, 1878.

Williamson's publication the original data are not given, but only the results of the computations as exhibited in a table of mean and extreme errors; but he has courteously furnished the writer a copy of the barometric readings and thus enabled him to apply his method of computation to them.

The observations in question were made at the hours of 7 a. m., 2 p. m., and 9 p. m., during ten days of the month of August, 1860, at three stations on the western slope of the Sierra Nevada. The positions of the stations, as given by Williamson on page 28 of his Manual, are as follows:

Station.	Latitude.	Longitude.	Altitude.
	° ′	° ′	Feet.
Placerville	38 44	120 46	1,965
Strawberry Valley	38 49	120 07	5,707
Hope Valley	38 47	119 54	7,072

From these data were deduced the following:

Stations.	Distance.	Difference of Altitude.
	Miles.	Feet.
Placerville to Strawberry Valley	35	3,742
Placerville to Hope Valley	46	5,107
Strawberry Valley to Hope Valley	12	1,365

These differences in altitude appear not to have been determined by the aid of the spirit level, but only by computations from the means of a large number of barometric observations. The errors found by Williamson in his computations from single pairs of observations are not to be regarded as absolute errors but rather as wanderings from the mean of many determinations, and therefore, in recomputing the altitudes and making a table of the errors incurred by the new system, I have compared each individual determination with the mean of its own series, instead of taking Williamson's mean determination as a standard. It would, of course, afford a better test of the comparative value of the two methods if the result of each individual computation were compared with an accurately-ascertained, authoritative value of the difference in altitude; but, in the absence of such a standard, the only practicable criterion of comparison is the internal harmony of the several series of results. A method which, on successive trials, gives nearly the same result is manifestly preferable to one which gives widely different results.

In the preparation of the observations for the application of the new formula no correction was made for the diurnal oscillation of the barometer, and, with a single exception, the readings were used with no modification other than the usual corrections for the temperatures and

index errors of the instruments. The exceptional case is that of the observation made at Strawberry Valley on the 17th of August, at 2 p. m., while a thunder storm was in progress. For this an interpolated reading was substituted.

Having three equally continuous series of observations, it was evidently possible to regard each of the three stations in turn as the new station and the other two as base stations, and this was accordingly done. The air column comprised between Placerville and Hope Valley, assumed to have a height of 5,107 feet, was first taken as a base line, and from it the altitude of the intermediate station, Strawberry Valley, was computed. Under the new method it is a matter of indifference whether the space between the new station and the upper base, or that between the new station and the lower base, is the quantity sought. But it is not so with Williamson's method, and a comparison is therefore made both with his determination of the difference in altitude between Placerville and Strawberry Valley and with his determination of the difference between Strawberry Valley and Hope Valley.

Table III exhibits the data for the computation, and the results. The first column shows the hours of observation; the next three give the synchronous readings of the barometer at the three stations; the fifth column contains the several determinations of the difference in altitude of the stations in Hope Valley and Strawberry Valley, and the seventh the corresponding determinations of the difference in altitude of the stations in Strawberry Valley and Placerville. The numbers in the sixth column were obtained by subtracting the mean of the numbers in the fifth from each of them, and exhibit the deviations of the individual results from the mean. It will be convenient to distinguish such deviations by the title "residual", reserving the word "error" to designate deviations from an absolute standard. The numbers of the eighth column are derived from those of the seventh in a similar manner. In the line beneath the columns their arithmetic means, taken regardless of sign, are given, and the numbers opposite the word "range" are derived in each case by adding the largest residual with the plus sign to the largest residual with the minus sign.

Strawberry Valley and Placerville were next taken as base stations, and from them the altitude of Hope Valley was computed. The assumed height of the base line was 3,742 feet, that being the altitude of Strawberry Valley above Placerville as given by Williamson; but it must be borne in mind that this quantity was itself determined by the use of the barometer, and is therefore presumably only approximate. Whatever error it involves must inhere in all results derived from it, affecting them all alike.

Hope Valley and Strawberry Valley were then taken as base stations, with an assumed difference of altitude of 1,365 feet, and from them the relative altitude of Placerville was computed. In the preceding case the

base line was nearly three times as long as the height determined by means of it; in this case the relations are reversed, the base line having scarcely more than one-third the magnitude of the distance computed.

TABLE III.

Differences of Altitude computed by New Method from Single Sets of Observations; New Station *intermediate* between Bases.

Day and Hour of Observation, 1860.	Barometer Readings.*			Hope Valley and Strawberry Valley.		Strawberry Valley and Placerville.	
	Placerville.	Strawberry Valley.	Hope Valley.	Alt.	Resid.	Alt.	Resid.
	Inches.	*Inches.*	*Inches.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*
Aug. 11—7 a. m.	28.009	24.597	23.417	1,391.7	+ 12.8	3,715.3	− 12.8
2 p. m.	.017	.562	.381	1,380.8	+ 1.9	3,726.2	− 1.9
9 p. m.	27.985	.544	.375	1,374.0	− 4.9	3,733.0	+ 4.9
Aug. 12—7 a. m.	.944	.471	.277	1,387.6	+ 8.7	3,719.4	− 8.7
2 p. m.	.958	.446	.261	1,369.1	− 9.8	3,737.9	+ 9.8
9 p. m.	.894	.440	.242	1,396.3	+ 17.4	3,710.7	− 17.4
Aug. 13—7 a. m.	.903	.446	.255	1,389.2	+ 10.3	3,717.8	− 10.3
2 p. m.	.861	.401	.230	1,371.2	− 7.7	3,735.8	+ 7.7
9 p. m.	.812	.406	.222	1,397.5	+ 18.6	3,709.5	− 18.6
Aug. 14—7 a. m.	.826	.387	.214	1,378.7	− 0.2	3,728.3	+ 0.2
2 p. m.	.823	.387	.202	1,390.1	+ 11.2	3,716.9	− 11.2
9 p. m.	.819	.420	.240	1,395.8	+ 16.9	3,711.2	− 16.9
Aug. 15—7 a. m.	.830	.438	.290	1,369.3	− 9.6	3,737.7	+ 9.6
2 p. m.	.852	.430	.291	1,353.0	− 25.9	3,754.0	+ 25.9
9 p. m.	.875	.483	.320	1,382.5	+ 3.6	3,724.5	− 3.6
Aug. 16—7 a. m.	.888	.493	.356	1,358.5	− 20.4	3,748.5	+ 20.4
2 p. m.	.877	.473	.324	1,366.8	− 12.1	3,740.2	+ 12.1
9 p. m.	.861	.494	.333	1,387.7	+ 8.8	3,719.3	− 8.8
Aug. 17—7 a. m.	.865	.485	.354	1,357.3	− 21.6	3,749.7	+ 21.6
2 p. m.	.820	[.465]	.319	1,377.9	− 1.0	3,729.1	+ 1.0
9 p. m.	.831	.460	.318	1,374.3	− 4.6	3,732.7	+ 4.6
Aug. 18—7 a. m.	.882	.474	.315	1,374.6	− 4.3	3,732.4	+ 4.3
2 p. m.	.855	.488	.341	1,375.3	− 3.6	3,731.7	+ 3.6
9 p. m.	.869	.469	.316	1,371.4	− 7.5	3,735.6	+ 7.5
Aug. 19—7 a. m.	.914	.497	.334	1,375.3	− 3.6	3,731.7	+ 3.6
2 p. m.	.925	.477	.323	1,359.2	− 19.7	3,747.8	+ 19.7
9 p. m.	.941	.532	.356	1,389.1	+ 10.2	3,717.9	− 10.2
Aug. 20—7 a. m.	28.016	.579	.395	1,388.2	+ 9.3	3,718.8	− 9.3
2 p. m.	.021	.570	.389	1,381.8	+ 2.9	3,725.2	− 2.9
9 p. m.	.023	.612	.420	1,402.4	+ 23.5	3,704.6	− 23.5
Mean				1,378.9	10.4	3,728.1	10.4
Range				....	49.4	....	49.4
Comparative results from Williamson:							
Mean				1,368.6	21.0	3,731.6	20.1
Range				....	90.2	....	194.5

*The barometer readings are from a manuscript copy of the original records furnished by Colonel Williamson, and are corrected for index error and temperature of instrument. The bracketed reading is interpolated. The comparative results in the lower line are derived from page 49 of his Compendium.

The results of the former series of computations appear in the second and third columns of Table IV; those of the latter series in the fourth and fifth columns.

TABLE IV.

Differences of Altitude Computed by New Method from Single Sets of Observations; New Station *not intermediate* between Base Stations.

Day and Hour of Observation. 1860.	Hope Valley and Strawberry Valley.		Strawberry Valley and Placerville.	
	Alt.	Resid.	Alt.	Resid.
	Feet.	*Feet.*	*Feet.*	*Feet.*
Aug. 11—7 a. m	1,401.7	+ 17.6	3,643.7	— 47.7
2 p. m	1,386.7	+ 2.6	3,683.0	— 8.4
9 p. m	1,377.4	— 6.7	3,708.4	+ 17.0
Aug. 12—7 a. m	1,396.0	+ 11.9	3,658.2	— 33.2
2 p. m	1,370.7	— 13.4	3,726.7	+ 35.3
9 p. m	1,407.9	+ 23.8	3,627.2	— 64.2
Aug. 13—7 a. m	1,398.2	+ 14.1	3,652.5	— 38.9
2 p. m	1,373.6	— 10.5	3,718.5	+ 27.1
9 p. m	1,409.6	+ 25.5	3,622.8	— 68.6
Aug. 14—7 a. m	1,383.8	— 0.3	3,709.8	+ 18.4
2 p. m	1,399.5	+ 15.4	3,649.3	— 42.1
9 p. m	1,407.2	+ 23.1	3,629.3	— 62.1
Aug. 15—7 a. m	1,370.9	— 13.2	3,726.0	+ 34.6
2 p. m	1,348.6	— 35.5	3,787.8	+ 96.4
9 p. m	1,389.1	+ 5.0	3,676.3	— 15.1
Aug. 16—7 a. m	1,356.1	— 28.0	3,767.0	+ 75.6
2 p. m	1,367.5	— 16.6	3,735.5	+ 44.1
9 p. m	1,396.2	+ 12.1	3,658.0	— 33.4
Aug. 17—7 a. m	1,354.4	— 29.7	3,771.8	+ 80.4
2 p. m	1,382.7	— 1.4	3,694.0	+ 2.6
9 p. m	1,377.8	— 6.3	3,707.6	+ 16.2
Aug. 18—7 a. m	1,378.1	— 6.0	3,706.6	+ 15.2
2 p. m	1,379.1	— 5.0	3,703.8	+ 12.4
9 p. m	1,373.8	— 10.3	3,717.8	+ 26.4
Aug. 19—7 a. m	1,379.4	— 4.7	3,702.9	+ 11.5
2 p. m	1,357.1	— 27.0	3,764.1	+ 72.7
9 p. m	1,398.1	+ 14.0	3,652.8	— 38.6
Aug. 20—7 a. m	1,396.9	+ 12.8	3,656.1	— 35.3
2 p. m	1,388.1	+ 4.0	3,679.2	— 12.2
9 p. m	1,416.2	+ 32.1	3,605.9	— 85.5
Mean	1,384.1	14.3	3,691.4	39.0
Range	....	67.6	....	181.9
Comparative results from Williamson:				
Mean	1,368.6	21.0	3,731.6	20.1
Range	....	90.2	....	194.5

Besides the results from the reduction of these August observations, Colonel Williamson has published a series of altitudes involving the same stations, based upon daily means of observations. They were not computed for the purpose of a comparative test, nor did he apply to them the formula published in his volume and of which he recommends the use. He applied, however, the formula of Guyot, which differs chiefly in failing to take separate account of the humidity of the atmos-

phere, and affords nearly the same results when applied to the means of daily sets of observations. His publication includes the observations as well as the computed altitudes, and selecting from them the series for July and January, I have made comparative computations of altitude by the method of two bases, hoping thereby to illustrate still further the relative value of the new method, and especially to ascertain whether its results are affected like those of other methods by variations depending upon the season of year. The results of the computations are given in Tables V, VI, VII, and VIII, where they are arranged side by side with those of Williamson.

TABLE V.

Differences of Altitude Computed from Daily Means. Hope Valley and Strawberry Valley. July, 1860.

Day of Month.	By Williamson, with Guyot's Formula.		By New Method, from—			
			Hope Valley and Placerville.		Strawberry Valley and Placerville.	
	Alt.	Resid.	Alt.	Resid.	Alt.	Resid.
	Feet.	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*
1	1,381	− 5	1,374.3	− 8.3	1,377.7	− 11.4
2	1,384	− 3	1,378.7	− 3.9	1,383.8	− 5.3
3	1,386	− 1	1,378.4	− 4.2	1,383.4	− 5.7
4	1,383	− 4	1,374.5	− 8.1	1,378.0	− 11.1
5	1,385	− 2	1,378.8	− 3.8	1,383.9	− 5.2
6	1,387	0	1,386.4	+ 3.8	1,394.4	+ 5.3
7	1,378	− 9	1,378.2	− 4.4	1,383.1	− 6.0
8	1,403	+ 16	1,396.4	+ 13.8	1,408.1	+ 19.0
9	1,415	+ 28	1,393.2	+ 10.6	1,403.6	+ 14.5
10	1,405	+ 18	1,371.4	− 11.2	1,373.9	− 15.2
11	1,390	+ 4	1,375.8	− 6.8	1,379.8	− 9.3
12	1,396	+ 9	1,379.9	− 2.7	1,385.5	− 3.6
13	1,400	+ 13	1,382.2	− 0.4	1,388.7	− 0.4
14	1,397	+ 10	1,386.8	+ 4.2	1,394.9	+ 5.8
15	1,399	+ 12	1,388.4	+ 5.8	1,397.0	+ 7.9
16	1,385	− 2	1,382.6	0.0	1,389.3	+ 0.2
17	1,383	− 4	1,384.5	+ 1.9	1,391.8	+ 2.7
18	1,407	+ 20	1,392.0	+ 9.4	1,402.1	+ 13.0
19	1,390	+ 3	1,385.9	+ 3.3	1,393.7	+ 4.6
20	1,391	+ 4	1,386.0	+ 3.4	1,393.8	+ 4.7
21	1,380	− 7	1,380.0	− 2.6	1,385.6	− 3.5
22	1,392	+ 5	1,383.1	+ 0.5	1,389.9	+ 0.8
23	1,391	+ 4	1,387.1	+ 4.5	1,395.4	+ 6.3
24	1,372	− 14	1,371.8	− 10.8	1,374.4	− 14.7
25	1,365	− 22	1,369.7	− 12.9	1,371.5	− 17.6
26	1,344	− 43	1,351.1	− 31.5	1,345.9	− 43.2
27	1,367	− 20	1,380.4	− 2.2	1,386.1	− 3.0
28	1,377	− 10	1,391.0	+ 8.4	1,400.8	+ 11.7
29	1,391	+ 4	1,396.4	+ 13.8	1,408.1	+ 19.0
30	1,384	− 3	1,399.4	+ 16.8	1,412.3	+ 23.2
31	1,386	− 1	1,395.5	+ 12.9	1,406.8	+ 17.7
Mean	1,387	10	1,382.6	7.3	1,389.1	10.1
Range	....	71	....	48.3	....	66.4

TABLE VI.

Differences of Altitude Computed from Daily Means. Strawberry Valley and Placerville. July, 1860.

Day of Month.	By Williamson, with Guyot's Formula.		By New Method, from— Hope Valley and Placerville.		By New Method, from— Hope Valley and Strawberry Valley.	
	Alt.	Resid.	Alt.	Resid.	Alt.	Resid.
	Feet.	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*
1	3,782	+ 24	3,732.7	+ 8.3	3,707.5	+ 31.1
2	3,761	+ 3	3,728.3	+ 3.9	3,691.0	+ 14.6
3	3,760	+ 2	3,728.6	+ 4.2	3,692.3	+ 15.9
4	3,775	+ 17	3,732.5	+ 8.1	3,688.0	+ 11.6
5	3,754	− 4	3,728.2	+ 3.8	3,690.5	+ 14.1
6	3,752	− 6	3,720.6	− 3.8	3,662.4	− 14.0
7	3,761	+ 3	3,728.8	+ 4.4	3,693.0	+ 16.6
8	3,765	+ 7	3,710.6	− 13.8	3,627.0	− 49.4
9	3,789	+ 31	3,713.8	− 10.6	3,638.4	− 38.0
10	3,827	+ 69	3,735.6	+ 11.2	3,717.8	+ 41.4
11	3,781	+ 23	3,731.2	+ 6.8	3,701.8	+ 25.4
12	3,794	+ 36	3,727.1	+ 2.7	3,686.5	+ 10.1
13	3,783	+ 25	3,724.8	+ 0.4	3,677.8	+ 1.4
14	3,758	0	3,720.2	− 4.2	3,661.0	− 15.4
15	3,760	+ 2	3,718.6	− 5.8	3,655.2	− 21.2
16	3,747	− 11	3,724.4	0.0	3,676.4	0.0
17	3,742	− 16	3,722.5	− 1.9	3,669.6	− 6.8
18	3,764	+ 6	3,715.0	− 9.4	3,642.2	− 34.2
19	3,758	0	3,721.1	− 3.3	3,664.3	− 12.1
20	3,760	+ 2	3,721.0	− 3.4	3,664.0	− 12.4
21	3,742	− 16	3,727.0	+ 2.6	3,686.2	+ 9.8
22	3,755	− 3	3,723.9	− 0.5	3,674.5	− 1.9
23	3,740	− 18	3,719.9	− 4.5	3,660.1	− 16.3
24	3,748	− 10	3,735.2	+ 10.8	3,716.3	+ 39.9
25	3,756	− 2	3,737.3	+ 12.9	3,724.3	+ 47.9
26	3,763	+ 5	3,755.9	+ 31.5	3,795.0	+118.6
27	3,730	− 28	3,726.6	+ 2.2	3,684.6	+ 8.2
28	3,714	− 44	3,716.0	− 8.4	3,646.3	− 30.1
29	3,734	− 24	3,710.6	− 13.8	3,626.9	− 49.5
30	3,718	− 40	3,707.6	− 16.8	3,616.2	− 60.2
31	3,725	− 33	3,711.5	− 12.9	3,630.0	− 46.4
Mean	3,758	16	3,724.4	7.8	3,676.4	26.3
Range	....	113	....	48.3	....	178.8

TABLE VII.

Differences of Altitude Computed from Daily Means. Hope Valley and Strawberry Valley. January, 1864.

Day of Month.	By Williamson, with Guyot's Formula.		By New Method, from—			
			Hope Valley and Placerville.		Strawberry Valley and Placerville.	
	Alt.	Resid.	Alt.	Resid.	Alt.	Resid.
	Feet.	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*
1	1,349	+ 6	1,359.2	− 3.6	1,357.1	− 4.9
2	1,396	+ 53	1,388.2	+ 25.4	1,396.9	+ 34.9
3	1,393	+ 50	1,387.2	+ 24.4	1,395.5	+ 33.5
4	1,374	+ 31	1,373.1	+ 10.3	1,376.2	+ 14.2
5	1,313	− 29	1,347.8	− 15.0	1,341.4	− 20.6
6	1,350	+ 7	1,364.3	+ 1.5	1,364.1	+ 2.1
7	1,350	+ 7	1,366.1	+ 3.3	1,366.5	+ 4.5
8	1,321	− 22	1,354.8	− 8.0	1,351.0	− 11.0
9	1,289	− 54	1,334.0	− 28.8	1,322.4	− 39.6
10	1,328	− 15	1,355.6	− 7.2	1,352.1	− 9.9
11	1,388	+ 45	1,379.9	+ 17.1	1,385.5	+ 23.5
12	1,370	+ 27	1,368.1	+ 5.3	1,369.3	+ 7.3
13	1,372	+ 29	1,370.9	+ 8.1	1,373.1	+ 11.1
14	1,395	+ 52	1,384.1	+ 21.3	1,391.2	+ 29.2
15	1,374	+ 31	1,376.2	+ 13.4	1,380.3	+ 18.3
16	1,300	− 42	1,348.5	− 14.3	1,342.3	− 19.7
17	1,316	− 27	1,354.6	− 8.2	1,350.8	− 11.2
18	1,324	− 18	1,363.3	+ 0.5	1,362.8	+ 0.8
19	1,302	− 41	1,355.5	− 7.3	1,352.0	− 10.0
20	1,321	− 22	1,366.5	+ 3.7	1,367.1	+ 5.1
21	1,320	− 22	1,361.0	− 1.8	1,359.5	− 2.5
22	1,321	− 22	1,345.6	− 17.2	1,338.4	− 23.6
23	1,250	− 93	1,317.2	− 45.6	1,299.4	− 62.6
24	1,278	− 65	1,333.1	− 29.7	1,321.2	− 40.8
25	1,311	− 32	1,350.6	− 12.2	1,345.2	− 16.8
26	1,351	+ 8	1,366.8	+ 4.0	1.367.5	+ 5.5
27	1,357	+ 14	1,359.8	− 3.0	1,357.9	− 4.1
28	1,362	+ 19	1,367.1	+ 4.3	1,367.9	+ 5.9
29	1,401	+ 58	1,394.4	+ 31.6	1,405.3	+ 43.3
30	1,383	+ 40	1,382.3	+ 19.5	1,388.8	+ 26.8
31	1,368	+ 25	1,371.7	+ 8.9	1,374.3	+ 12.3
Mean	1,343	33	1,362.8	13.0	1,362.0	17.9
Range	....	151	....	77.2	....	105.9

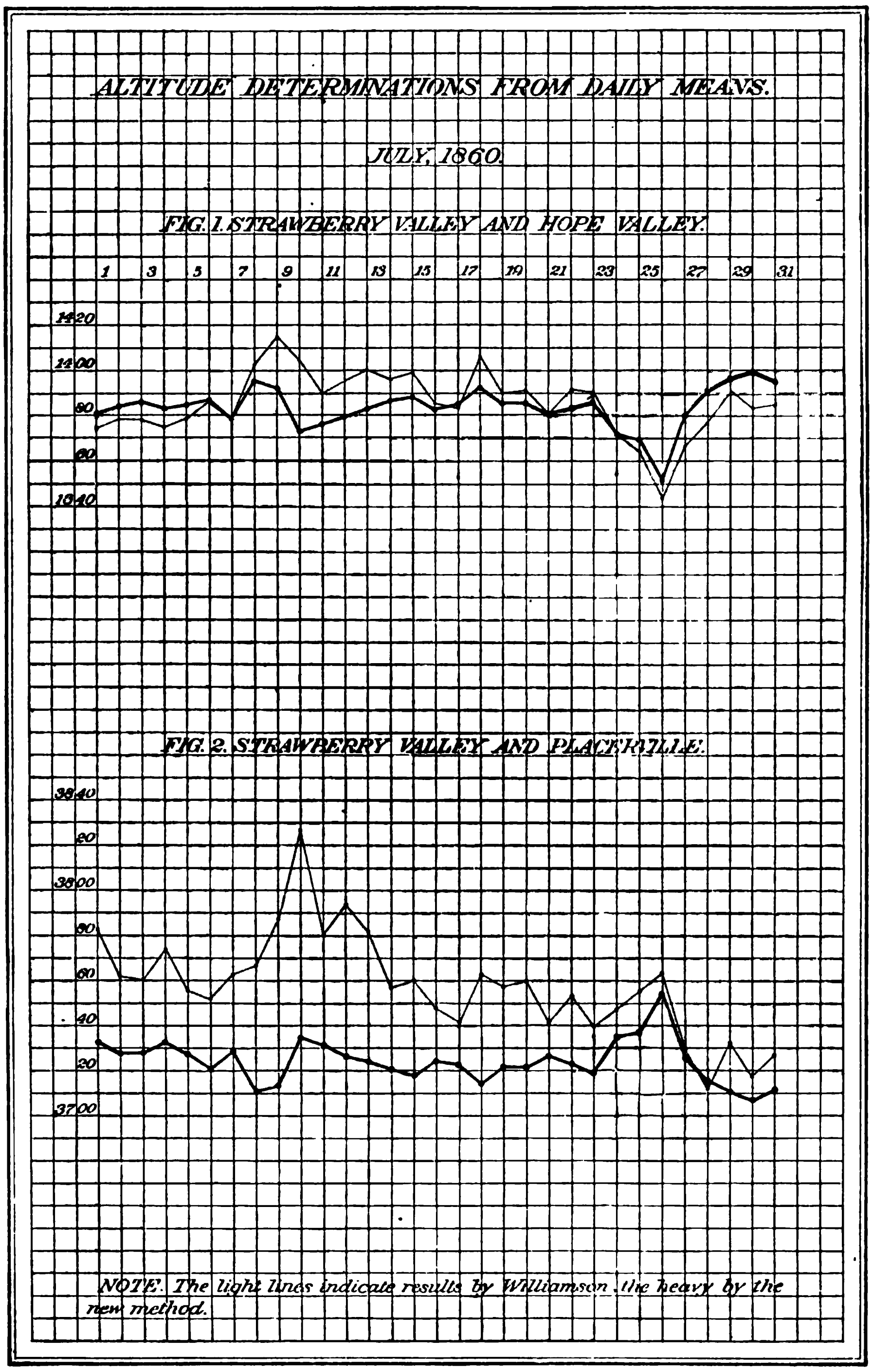
TABLE VIII.

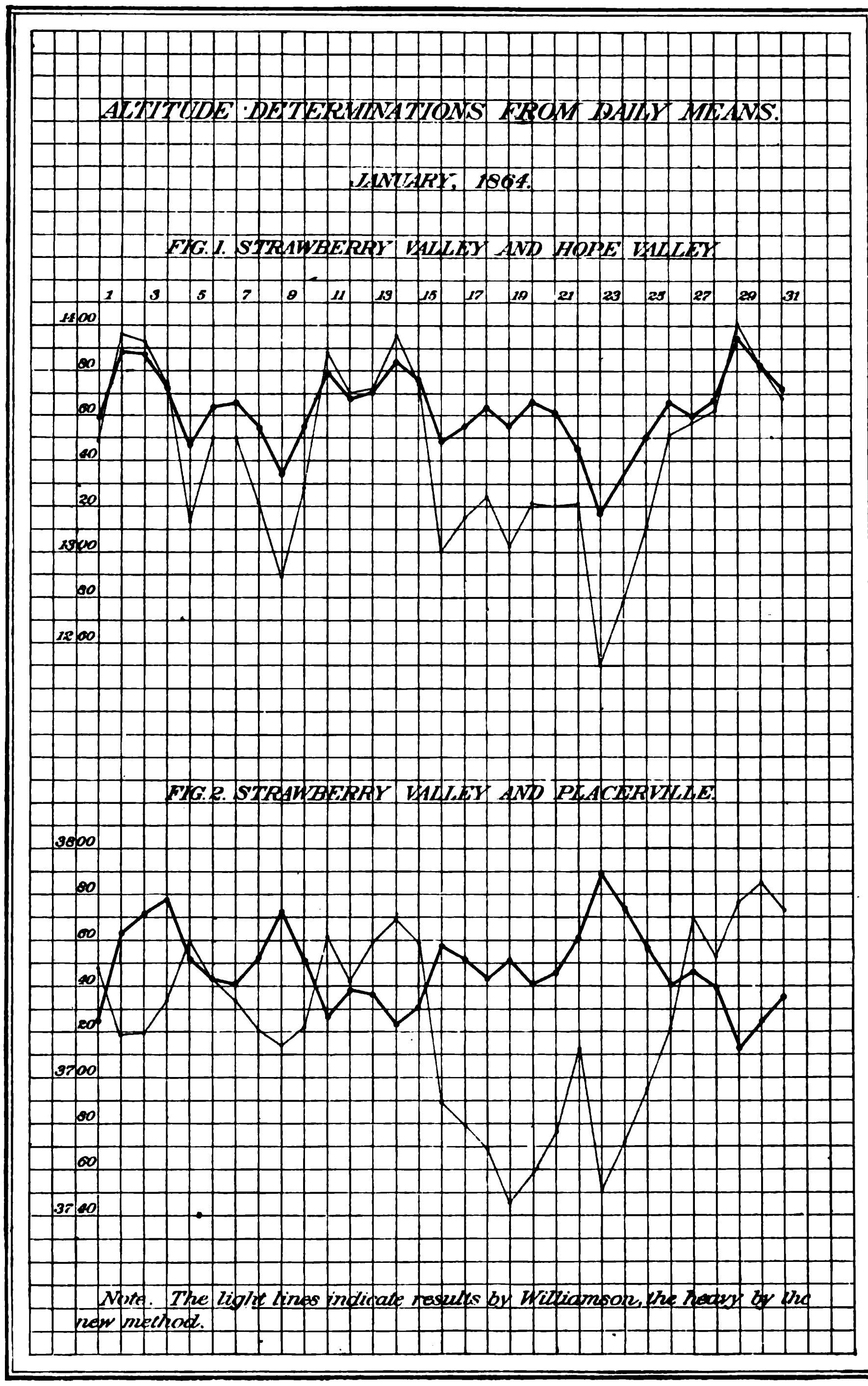
Differences of Altitude Computed from Daily Means. Strawberry Valley and Placerville. January, 1864.

Day of Month.	By Williamson, with Guyot's Formula.		By New Method, from—			
			Hope Valley and Placerville.		Hope Valley and Strawberry Valley.	
	Alt.	Resid.	Alt.	Resid.	Alt.	Resid.
	Feet.	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*
1	3,725	− 1	3,747.8	+ 3.6	3,764.2	− 13.1
2	3,763	+ 36	3,718.8	− 25.4	3,656.0	− 95.1
3	3,771	+ 44	3,719.8	− 24.4	3,659.7	− 91.4
4	3,777	+ 50	3,733.9	− 10.3	3,711.6	− 39.5
5	3,751	+ 24	3,759.2	+ 15.0	3,807.7	+ 56.6
6	3,744	+ 17	3,742.7	− 1.5	3,744.4	− 6.7
7	3,733	+ 6	3,740.9	− 3.3	3,738.1	− 13.0
8	3,720	− 7	3,752.2	+ 8.0	3,781.0	+ 29.9
9	3,714	− 12	3,773.0	+ 28.8	3,861.5	+ 110.4
10	3,721	− 6	3,751.4	+ 7.2	3,778.0	+ 26.9
11	3,761	+ 34	3,727.1	− 17.1	3,686.6	− 64.5
12	3,742	+ 15	3,738.9	− 5.3	3,730.5	− 20.6
13	3,759	+ 32	3,736.1	− 8.1	3,719.8	− 31.3
14	3,769	+ 43	3,722.9	− 21.3	3,671.0	− 80.1
15	3,759	+ 32	3,730.8	− 13.4	3,700.5	− 50.6
16	3,689	− 38	3,758.5	+ 14.3	3,805.0	+ 53.9
17	3,679	− 47	3,752.4	+ 8.2	3,781.8	+ 30.7
18	3,669	− 58	3,743.7	− 0.5	3,748.3	− 2.8
19	3,646	− 81	3,751.5	+ 7.3	3,778.5	+ 27.4
20	3,659	− 67	3,740.5	− 3.7	3,736.6	− 14.5
21	3,677	− 50	3,746.0	+ 1.8	3,757.1	+ 6.0
22	3,712	− 15	3,761.4	+ 17.2	3,815.4	+ 64.3
23	3,651	− 76	3,789.8	+ 45.6	3,928.3	+ 177.2
24	3,671	− 56	3,773.9	+ 29.7	3,865.0	+ 113.9
25	3,694	− 33	3,756.4	+ 12.2	3,797.0	+ 45.9
26	3,721	− 5	3,740.2	− 4.0	3,735.5	− 15.6
27	3,769	+ 42	3,747.2	+ 3.0	3,761.8	+ 10.7
28	3,753	+ 27	3,739.9	− 4.3	3,734.3	− 16.8
29	3,776	+ 49	3,712.6	− 31.6	3,634.2	− 116.9
30	3,784	+ 57	3,724.7	− 19.5	3,677.4	− 73.7
31	3,772	+ 45	3,735.3	− 8.9	3,717.0	− 34.1
Mean	3,727	36	3,744.2	13.0	3,751.1	49.5
Range	....	138	....	77.2	....	294.1

In Tables V and VI the results for July appear; in Tables VII and VIII the results for January. Tables V and VII give determinations of the height of Hope Valley above Strawberry Valley; Tables VI and VIII of the height of Strawberry Valley above Placerville. In each table Williamson's values appear at the left and are succeeded, first, by the values computed from the base line given by Hope Valley and Placerville, and, second, by the values computed from a shorter base.

A selection from the same results is graphically exhibited in the curves of Plates LIV and LV.


ALTITUDE DETERMINATIONS FROM DAILY MEANS.
JULY, 1860.
FIG. 1. STRAWBERRY VALLEY AND HOPE VALLEY.
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31
1420
1400
80
60
1040
FIG. 2. STRAWBERRY VALLEY AND PLACERVILLE.
3840
20
3800
80
60
40
20
3700
NOTE. The light lines indicate results by Williamson, the heavy by the new method.


ALTITUDE DETERMINATIONS FROM DAILY MEANS.
JANUARY, 1864.
FIG. 1. STRAWBERRY VALLEY AND HOPE VALLEY.
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31
1400 80 60 40 20 1300 80 1260
FIG. 2. STRAWBERRY VALLEY AND PLACERVILLE.
3800 80 60 40 20 3700 80 60 3740
Note. The light lines indicate results by Williamson, the heavy by the new method.

It has been proposed to designate the height of the air column included between the two base stations as the "vertical base", or the "base line". It will be convenient to add a parallel term and call the height of the air column included between the new station and that base station to which it is referred, the *new line*. If we represent by the positions of the letters H, S, and P of the diagram, the vertical relations of the stations in Hope Valley, Strawberry Valley, and Placerville, then when Hope Valley and Placerville are used as base stations, the line H P becomes the base line, and either H S or S P the new line. When H S is taken as the base line and H P or S P is the new line, it is evident that every error which affects the barometric reading at H or S, and thereby affects the approximate determination of the base line H S, must appear in a magnified form in the corresponding determination of the new line; but when the new line is shorter than the base line the reverse holds true, and errors affecting the base line produce relatively small errors in the determination of the new line. The most favorable circumstances for the application of the method are therefore those in which the base line is greater than the new line, and this is always the case when the new station is intermediate in altitude between the two bases.

It will be proper, therefore, in making a general comparison of results, to distinguish those cases in which the new line is shorter than the base line from the less favorable cases in which it is longer.

In Table IX the results of Williamson's computations are compared with the best results by the new method—that is, with those obtained by the employment of a base line longer than the new line.

By the new method the same degree of accuracy, and indeed the same result, is obtained by regarding either H S or S P as the new line; but by Williamson's method the case is different, and two columns are therefore given for his results, the first for the case in which the computed height is about 1,365 feet, and the second for the case in which it is about 3,742 feet.

Two measures of precision are also indicated, the range of variation, and the mean of residuals, or the average residual. It goes without saying that a poor method will ordinarily exhibit a greater difference between its extreme results than a good one; but since extreme results are sometimes due to accidents altogether anomalous and exceptional, the rule does not invariably hold true. The arithmetic mean of residuals is a better criterion, for the amount of error or variation which by experiment is found to accrue *on the average* is a measure of the amount to be anticipated in future applications of the same method. In this case it happens that the general indication is the same by either criterion.

TABLE IX.

Comparison of Results for the case of a New Station *intermediate* in Altitude between two Base Stations.

Observations.	Range of Computed Results.			Average Deviation of Individual Results from the Mean.		
	By Williamson.		By New Method.	By Williamson.		By New Method.
	Computed Height.			Computed Height.		
	1,365 feet.	3,742 feet.		1,365 feet.	3,742 feet.	
	Feet.	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*
Thirty Individual Hours in August, 1860	90	194	49	21	20	10
Daily Means for July, 1860	71	113	48	10	16	7
Daily Means for January, 1864	151	138	77	33	36	13
Ratios	1.00		.47	1.00		.47

The ratios at the bottom of the table were derived by first taking the corresponding ratios in each line and then deducing their means. They indicate that by the application of the new method under favorable conditions the variation of results among themselves is reduced one-half, and they warrant the presumption that there is an absolute diminution of hypsometric error by the same amount. In the absence of an absolute standard, and so long as the individual computed altitudes can only be compared with a mean of altitudes barometrically determined, it is impossible to say that there are no constant errors which fail to be eliminated; but so far as the evidence goes it points to the advantage of the additional base station.

Turning now to the less favorable case in which the new station is not intermediate between the two bases, we find a less favorable result. With the line S P as a base, we might regard either H P or H S as the new line, but since Colonel Williamson has computed values for the shorter only of these lines, our comparison is necessarily restricted to that.

Table X gives first the results obtained by Williamson for the line H S, and compares with them the results by the new method, the line S P being used as a base. It then gives the results obtained by Williamson for the line S P, and contrasts them with results by the new method, the line H S being used as a base. The second case is manifestly the less favorable for the new method, because it determines a long new line from a short base line, and this difference is strikingly exhibited by the numerical ratios. With a relatively long base line the new method diminishes the mean residual one-fourth; with a relatively short base line it increases it two-thirds. We may therefore say without hesitation that the new method should not be applied to new stations falling outside the base line and separated from its nearest extremity by a

vertical space greatly exceeding the length of the base line. And we may further say that for all stations falling outside the base line the advantage of the new method is less than for stations between the bases. The data are too meager, however, to enable us to indicate the precise ratio of new line to base line at which the applicability of the method finds its limit.

TABLE X.

Comparison of Results for the case of a New Station *not intermediate* in Altitude between two Base Stations.

Observations.	Range of Computed Results.				Average Deviation of Individual Results from the Mean.			
	Computed Height, 1,365 ft.		Computed Height, 3,742 ft.		Computed Height, 1,365 ft.		Computed Height, 3,742 ft.	
	By Williamson.	By New Method; base = 3,742 feet.	By Williamson.	By New Method; base = 1,365 feet.	By Williamson.	By New Method; base = 3,742 feet.	By Williamson.	By New Method; base = 1,365 feet.
	Feet.	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*
Thirty Individual Hours in Aug., 1860.	90	68	194	182	21	14	20	39
Daily Means for July, 1860	71	66	113	179	10	10	16	26
Daily Means for January, 1864 ..	151	106	138	294	33	18	36	50
Ratios	1.00	.80	1.00	1.55	1.00	.74	1.00	1.66

It should be noted that in this comparison computation by the old method is made only of the distance between the new station and that base station lying nearest to it. Undoubtedly if we were able to examine results in which the more remote base station was the one used, the old method would appear to less advantage.

Yet another interesting comparison is afforded by the computations. It has been pointed out by many investigators that the results obtained in winter are different from those obtained in summer, being for some localities relatively high and for others relatively low. If these discrepancies depend upon the difficulty of determining the temperature of the air column by means of the thermometer, then theoretically they should be eliminated by the new method, and approximately the same mean results should be obtained at all times of the year—provided, always, the stations are so situated that the element of gradient does not largely enter. The stations in this case are so widely separated that the influence of gradient undoubtedly affects all the results, but it is nevertheless interesting to make the comparison. For this purpose the means of all the computed altitudes are assembled in Table XI. The second column gives the results for the period from August 11 to August 20, 1860; the third for the month of July, 1860; the fourth for the month of January, 1864. The remaining columns show the means of

the quantities in these three and their range. The upper division of the table is devoted to determinations of the altitude of Hope Valley above Strawberry Valley, and the lower to determinations of the altitude of Strawberry Valley above Placerville, each giving, first, the determination by Williamson, second, the determination by the new method applied with the new station intermediate between the two bases, and third, the determination by the new method applied with the new station outside the space included by the bases. Here, again, the superiority of the new method, when favorably conditioned, is shown. The determinations of the middle station, obtained by referring it to the highest and lowest as bases, have a range in the three months of only 20 feet, while Williamson's determinations show a range of 44 feet when the upper station is taken as the base, and of 31 feet when the lower is taken. Here too the most discordant determinations of all are those obtained by the new method when the new line is longer than the base line and lies entirely without it: the results of the computation of Placerville from Strawberry Valley and Hope Valley exhibit a range of 75 feet.

TABLE XI.

Comparison of Means of Altitude Determinations.

	Ten Days in August, 1860.	July, 1860.	January, 1864.	Mean.	Range.
	Feet.	*Feet.*	*Feet.*	*Feet.*	*Feet.*
Hope Valley and Strawberry Valley:					
By Williamson	1,369	1,387	1,343	1,366	44
By New Method:					
Base=5,107 feet	1,379	1,383	1,363	1,375	20
Base=3,742 feet	1,384	1,389	1,362	1,378	27
Strawberry Valley and Placerville:					
By Williamson	3,732	3,758	3,727	3,739	31
By New Method:					
Base=5,107 feet	3,728	3,724	3,744	3,732	20
Base=1,365 feet	3,691	3,676	3,751	3,706	75

The data are too meager for generalization, but so far as they go their indication is favorable to the new method. Williamson's records and discussions show that the month of January, 1864, was characterized in California by storms, while the month of July, 1860, and the ten days selected in August, were not so characterized. It is therefore possible, if not indeed probable, that the residuum of 20 feet, which the best application of the new method fails to eliminate from the disparity of the results for July and January, is largely due to the gradients accompanying the January storms.

It will be noted that the determinations by the new method of the difference of altitude of the two upper stations is almost uniformly greater than by the old, while the determination of the difference be-

tween the two lower stations is almost uniformly less. The deficit in the one case is the correlative of the excess in the other, for any influence which tends to raise the estimate by the new method of the one distance, tends at the same time to lower the estimate of the other. In the absence of an absolute standard it is impossible to refer the discrepancy to one method or the other. In applying the new method, the mean altitudes obtained by the old method, as given by Williamson, were accepted as the basis of computation, and whatever errors they involve have been not only retained but slightly exaggerated.

COMPARISON WITH WHITNEY'S METHOD.

In the year 1870 Professor J. D. Whitney, at that time State Geologist of California, instituted a series of barometric and thermometric observations at three stations upon the western slope of the Sierra Nevada, and the observations were continued for about three years. In a report to the legislature,* to which we have already had occasion to refer, he discusses these observations and bases upon them a series of hypsometric tables and a hypsometric system. The three stations were Sacramento, Colfax, and Summit, all upon the line of the Central Pacific Railroad and determined in altitude by the railroad surveys. Their relations in distance and altitude are as follows:

Stations.	Distance.	Difference of Altitude.
	Miles.	*Feet.*
Sacramento to Colfax	45	2,399
Colfax to Summit	36	4,590
Sacramento to Summit	77	6,989

Their latitude is about 39°. The observations were made daily at the hours of 7 a. m., 2 p. m., and 9 p. m., and from them Whitney derived monthly means for each hour. From these means of pressure and temperature he computed the difference in altitude of each pair of stations for each month of the three years and for each hour of observation, using Williamson's tables for the purpose, but neglecting the correction for humidity.

Comparing the results of these computations with the known differ-

* "Geological Survey of California. J. D. Whitney, State Geologist. Contributions to Barometric Hypsometry, with Tables for Use in California. Published by Authority of the Legislature. 1874."

The title page does not announce the author of the volume. The "Prefatory Note" is signed with Professor Whitney's initials, but speaks of the volume as "prepared by" Prof. W. H. Pettee, and conveys an impression of joint authorship. It is therefore with a constant reservation in favor of Professor Pettee that I have referred to the book and the hypsometric method as Professor Whitney's.

ences of altitude, he made tables of errors for each year and for each pair of stations. The series of errors he found to be similar in the different years, but not the identical, and, making allowances for their irregularities, he deduced from them a system of corrections which he embodied in tables. The first of these tables is entitled "Corrections to be applied for each thousand feet from sea-level to 2,400 feet," and gives a separate factor for each month of the year and each hour of the day from 7 a. m. to 9 p. m., inclusive; the second table gives similar "Corrections to be applied for each thousand feet from sea-level to 7,000 feet"; and the third gives "Corrections to be applied for each thousand feet of difference of level between the altitudes 2,400 feet and 7,000 feet." For the application of these tables, Professor Whitney directs that the altitude of a new station above the base station shall be first computed by means of some such tables as Williamson's or Guyot's, but without the application of a correction for moisture, and that to the result the factor from some one of his tables shall be added, the particular table being determined by the positions and altitudes of the two stations.

These tables are not intended for universal application, but merely for the neighborhood, largely considered, in which the observations on which they are based were made. Similar tables prepared by others in other climates, differ widely in the amount of correction to be applied at different hours and seasons, and no one table or group of tables can possibly be used to advantage in all parts of the world. Professor Whitney takes pains to define this limitation, claiming no value for his tables outside of California, and saying that "in order to obtain the best results the world over, it will be necessary to have similar tables for each mountain region." His method thus demands for its application a large preliminary outlay in each district; and if the comparatively inexpensive system here proposed can be shown to equal his in precision of result, it will be entitled to preference on economic grounds.

Comparative tests have been made in three ways: by computing the altitude of Colfax from monthly means; by computing it from single observations; and by computing the altitudes of other points in California. They will be described in the order named.

I. In the preparation of his tables Whitney was unable to make his correction for any particular hour and month the precise equivalent of the corresponding error in *each* year, because those errors in the three years were different. There is, therefore, for each individual date a discrepancy between the correction he proposes and the error he wishes to eradicate; so that when his own tables are applied to the observations from which they were derived they do not produce for individual months a perfect result. Nevertheless, we must suppose that they were adjusted as closely as was practicable, so that, after applying his corrections to the original observations, the residual errors are approximately at a minimum. Certainly, in the application of his tables to the differ-

ences in height of Sacramento, Colfax, and Summit, a selection is made of the conditions most likely to display his method to advantage.

To render the comparison as just as practicable, the new method has been applied only under *its* most favorable condition,—the condition, that is, that the new station is intermediate in altitude between the two base stations. Sacramento and Summit were taken as bases, and from them the altitude of Colfax was computed for each month and hour of observation.*

Whitney's series includes parts of the years 1870 and 1873, and the whole of 1871 and 1872. For the purpose of comparison the entire years only were used.

For each month and each hour of observation Whitney has computed, by means of Williamson's tables, the height of Colfax above Sacramento, and his results are published on pages 75 and 76 of his volume. Similar results for the difference in altitude of Colfax and Summit are published on pages 78 and 79. To each of these results the writer has added the appropriate correction from Whitney's special table, so as to give for each month and hour the result by Whitney's method. He has then subtracted from each of these results the altitude as determined by level, and called the difference an error. These errors, for the years 1871 and 1872, appear in the first four columns of Table XII. The corresponding errors, deduced in the same manner from the results by the new method, appear in the two columns at the right. The footings show that the mean error in the determination of Colfax by the new method is about the same as by Whitney's method. Whitney's error is slightly greater if Summit is taken as base station, and slightly smaller if Sacramento is taken.

II. The published observations give only the monthly means of the readings at the three stations, but Professor Whitney has done me the favor to place the original records at my service, and I have thus been enabled to base a second test upon series of single observations. For this purpose the observations at the three stations for the month of November, 1870, were employed, their selection being determined by the accidental fact that of all the records which came into my hands the set for that month was most nearly complete.

Table XIII contains a copy of the original figures, excepting, first, that the barometric readings have been corrected for temperature of instrument; and, second, that in every case where an observation is lacking from the record all other observations at the same hour are omitted. There remain eighty-six sets of observations, giving simultaneous pressures and temperatures at the three stations.

* The data for the computations are published on pages 32, 33, and 34 of the Californian "Contributions to Barometric Hypsometry."

TABLE XII.

Determination of the Altitude of Colfax, California, from Monthly Means. Comparison of Errors by Different Methods of Computation.

Month and Hour.	By Whitney's Method, the Base Station being—				By New Method from Summit and Sacramento.	
	Summit.		Sacramento.			
	1871.	1872.	1871.	1872.	1871.	1872.
	Feet.	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*
Jan. —7 a. m.	+ 24.8	− 0.9	− 14.7	+ 4.3	+ 2.5	+ 8.2
2 p. m.	+ 11.8	− 2.8	− 0.9	− 1.1	+ 2.9	− 1.9
9 p. m.	+ 21.1	− 5.1	− 17.6	+ 8.8	− 8.2	+ 3.7
Feb. —7 a. m.	+ 28.4	− 47.7	− 8.2	+ 3.2	− 4.0	− 21.2
2 p. m.	+ 6.2	+ 3.2	+ 3.0	− 8.1	− 11.9	− 20.1
9 p. m.	+ 19.8	− 57.6	+ 13.5	− 4.2	+ 3.6	− 28.1
Mar. —7 a. m.	+ 9.4	− 8.6	− 6.6	+ 7.1	− 2.9	+ 2.3
2 p. m.	+ 2.5	+ 8.0	− 1.0	− 12.1	− 5.7	− 10.8
9 p. m.	+ 17.0	− 25.2	+ 0.9	− 3.9	− 14.5	− 18.7
Apr. —7 a. m.	− 16.1	− 1.6	− 30.1	+ 10.8	− 10.9	+ 6.1
2 p. m.	− 18.0	+ 12.0	− 7.7	− 13.6	− 11.0	− 15.3
9 p. m.	+ 30.9	− 9.6	− 30.5	− 11.4	− 16.1	− 14.4
May —7 a. m.	− 23.5	+ 12.4	− 10.1	+ 3.0	+ 15.8	+ 17.3
2 p. m.	+ 1.5	+ 22.6	− 0.7	− 14.4	+ 6.7	− 5.6
9 p. m.	+ 30.8	+ 1.1	− 0.4	− 16.4	+ 8.9	− 7.8
June —7 a. m.	− 27.8	− 1.8	− 15.2	− 4.5	+ 18.6	+ 18.6
2 p. m.	− 1.9	+ 7.9	+ 5.4	− 44.6	+ 17.6	− 18.5
9 p. m.	+ 14.8	+ 5.6	− 22.3	− 22.3	− 2.2	− 8.2
July —7 a. m.	+ 4.7	+ 0.3	− 6.3	+ 17.8	+ 37.4	+ 39.3
2 p. m.	− 4.6	+ 11.2	+ 3.0	− 5.8	+ 15.0	+ 8.2
9 p. m.	+ 15.5	+ 0.6	− 2.8	− 4.1	+ 10.6	+ 5.7
Aug. —7 a. m.	+ 19.7	+ 12.0	− 3.2	+ 1.1	+ 33.9	− 7.0
2 p. m.	− 15.3	− 15.6	+ 8.8	− 15.0	+ 10.7	− 14.3
9 p. m.	+ 34.3	+ 16.4	− 6.7	− 13.5	+ 3.3	− 13.3
Sept.—7 a. m.	+ 3.9	− 4.2	+ 4.6	− 2.7	+ 23.7	− 4.1
2 p. m.	+ 6.8	− 1.1	+ 20.5	− 24.8	+ 15.5	− 21.3
9 p. m.	+ 23.0	− 22.2	+ 1.6	− 4.2	− 1.5	− 14.9
Oct. —7 a. m.	+ 12.7	− 28.8	+ 3.8	− 3.5	+ 18.1	− 0.5
2 p. m.	− 4.8	− 25.9	+ 16.8	− 24.7	+ 10.0	− 20.9
9 p. m.	+ 14.5	− 45.6	+ 3.9	− 25.7	+ 2.1	− 30.5
Nov. —7 a. m.	− 25.3	+ 7.3	− 2.2	+ 17.8	− 4.7	+ 28.3
2 p. m.	− 12.2	− 8.1	+ 1.8	− 3.8	− 8.6	+ 0.7
9 p. m.	− 27.3	+ 1.3	+ 3.4	− 6.6	− 14.0	− 4.9
Dec. —7 a. m.	− 45.1	+ 5.1	+ 14.8	− 10.4	− 0.9	+ 0.1
2 p. m.	− 29.3	+ 5.4	− 35.3	− 32.1	− 7.0	+ 5.7
9 p. m.	− 43.6	+ 6.9	+ 15.8	− 25.2	+ 7.2	− 1.9
Mean	18.0	12.5	9.6	12.0	11.0	12.3
Range	79.4	80.2	55.8	62.4	51.4	69.8
Mean of two years	15.2		10.8		11.6	
Range	91.9		65.1		69.8	

TABLE XIII.

Observations at Sacramento, Colfax, and Summit, California, during the Month of November, 1870. (Whitney.)

Day.	Hours.	Barometer (reduced).			Thermometer (Fahr.)		
		Sacramento.	Colfax.	Summit.	Sacramento.	Colfax.	Summit.
		Inches.	*Inches.*	*Inches.*	°	°	°
1	7 a. m	30.046	27.523	23.304	40.0	49.0	26.8
	2 p. m	29.984	.488	.260	73.0	74.0	49.6
	9 p. m	.994	.499	.272	55.5	56.5	32.8
2	7 a. m	30.096	.546	.272	55.0	48.5	27.5
	2 p. m	.089	.519	.235	67.0	63.0	46.8
	9 p. m	.092	.568	.245	55.0	51.5	37.2
3	7 a. m	.124	.575	.241	42.5	45.0	27.6
	2 p. m	.085	.563	.247	64.0	61.5	46.6
	9 p. m	.114	.579	.276	50.5	48.5	29.4
4	2 p. m	.157	.597	.201	63.0	55.5	41.0
	9 p. m	.132	.586	.198	52.5	46.5	29.4
5	7 a. m	.104	.547	.189	48.5	46.0	30.2
	2 p. m	.072	.529	.121	62.0	57.0	42.6
	9 p. m	29.938	.400	.067	50.0	47.5	32.0
6	7 a. m	.833	.284	22.901	45.0	42.5	31.4
	2 p. m	.817	.261	.851	58.5	43.5	26.2
	9 p. m	.892	.364	.900	46.5	38.5	23.4
7	7 a. m	30.038	.446	.984	40.5	40.0	21.4
	2 p. m	.087	.489	23.029	49.0	40.0	26.6
	9 p. m	.180	.622	.187	48.0	41.5	26.2
8	7 a. m	.246	.662	.276	41.5	38.0	12.8
	2 p. m	.160	.622	.260	56.0	55.0	40.6
	9 p. m	.124	.532	.221	46.0	41.0	24.4
9	7 a. m	.069	.510	.128	39.0	42.5	27.2
	2 p. m	.024	.461	.059	57.0	49.5	31.2
	9 p. m	.078	.512	.119	47.0	43.0	23.3
10	7 a. m	.174	.603	.321	37.0	37.0	17.8
	9 p. m	.190	.641	.323	45.0	44.5	28.3
11	7 a. m	.194	.639	.318	37.0	42.0	33.5
	2 p. m	.160	.601	.326	60.0	60.0	47.0
	9 p. m	.122	.589	.323	49.5	51.0	34.2
12	7 a. m	.123	.570	.299	40.0	45.0	28.2
	2 p. m	.063	.524	.283	64.0	65.0	47.4
	9 p. m	.050	.510	.287	49.5	51.0	32.4
13	7 a. m	.079	.536	.322	37.5	45.5	33.4
	2 p. m	.053	.540	.376	63.0	65.0	49.0
	9 p. m	.084	.517	.421	49.5	51.0	38.0
14	7 a. m	.144	.476	.453	39.0	48.5	35.0
	2 p. m	.103	.530	.438	68.0	64.0	49.2
	9 p. m	.103	.612	.440	50.0	50.0	38.2
15	7 a. m	.148	.647	.441	41.0	50.5	32.3
	2 p. m	.113	.609	.408	65.0	69.5	53.0
	9 p. m	.085	.607	.412	55.0	56.5	37.8
16	7 a. m	.062	.609	.411	42.5	56.0	38.0
	2 p. m	.074	.576	.374	70.0	75.0	54.0
	9 p. m	.087	.611	.416	51.5	57.0	37.2
17	2 p. m	.172	.673	.474	69.5	74.5	54.2
	9 p. m	.234	.747	.546	51.0	56.5	39.0

TABLE XIII—Continued.

Day.	Hour.	Barometer (reduced).			Thermometer (Fahr.)		
		Sacramento.	Colfax.	Summit.	Sacramento.	Colfax.	Summit.
		Inches.	*Inches.*	*Inches.*	°	°	
18	7 a. m	.308	.797	.541	43.0	51.5	37.5
	2 p. m	.234	.789	.591	69.0	73.0	53.2
	9 p. m	.284	.780	.597	52.0	56.0	30.3
19	7 a. m	.270	.742	.572	41.5	54.0	35.8
	9 p. m	.223	.720	.518	51.0	58.0	46.3
20	7 a. m	.243	.731	.473	44.0	51.5	34.0
	2 p. m	.186	.708	.513	71.0	73.0	48.2
	9 p. m	.211	.734	.536	52.0	57.5	36.4
21	7 a. m	.297	.796	.555	38.0	51.0	31.5
	2 p. m	.235	.720	.534	69.0	74.0	46.0
	9 p. m	.194	.707	.542	52.5	56.0	43.4
22	7 a. m	.176	.691	.516	37.5	51.0	34.4
	2 p. m	.140	.641	.450	67.0	74.5	52.3
	9 p. m	.124	.686	.449	48.0	55.0	36.0
23	7 a. m	.154	.652	.434	40.0	52.5	31.4
	2 p. m	.024	.646	.408	65.0	73.0	51.4
	9 p. m	.171	.672	.426	50.0	53.5	34.2
24	7 a. m	.240	.723	.462	44.0	50.0	32.6
	2 p. m	.195	.697	.433	69.0	68.0	51.4
	9 p. m	.226	.725	.468	51.5	54.0	31.2
25	7 a. m	.226	.696	.430	40.5	49.5	30.0
	2 p. m	.146	.573	.360	66.0	66.0	52.0
	9 p. m	.084	.586	.298	52.0	52.0	38.3
26	7 a. m	.012	.486	.124	44.0	46.0	34.0
	2 p. m	29.964	.405	.023	58.0	53.0	32.2
	9 p. m	30.009	.425	.051	48.0	50.0	25.3
27	7 a. m	.060	.469	.119	43.0	40.5	23.0
	2 p. m	.030	.467	.152	60.5	56.0	33.4
	9 p. m	.054	.529	.181	48.0	49.0	19.4
28	7 a. m	.114	.540	.193	36.5	36.0	19.0
	2 p. m	.066	.505	.161	58.0	54.0	34.0
	9 p. m	.050	.506	.188	50.0	50.0	32.4
29	7 a. m	.076	.531	.181	47.0	48.0	31.2
	2 p. m	.115	.603	.189	49.0	43.0	26.5
	9 p. m	.164	.626	.218	48.0	43.5	28.5
30	7 a. m	.182	.629	.234	47.0	44.5	28.0
	2 p. m	.156	.601	.248	54.0	56.0	35.2
	9 p. m	.113	.554	.249	48.5	47.5	29.0

From each set of observations the altitude of Colfax was computed three times: first, by Whitney's method with Summit as the reference or base station; second, by the same method with Sacramento as base station; and third, by the new method with Summit and Sacramento as joint bases.

Since the computations by Whitney's method were not made under his supervision, and since his instructions for the application of his method

leave a certain latitude to the computer, it is proper to define precisely the manner in which the work was done. A first approximate altitude was in each case computed by means of Williamson's table marked D_1.* A correction for temperature was then obtained by subtracting 64 degrees (F.) from the sum of the observed temperatures, dividing the remainder by 900, and multiplying the resulting quotient by the approximate altitude; and this correction was applied to the approximate altitude. A number expressing the sum of the corrections due to the variations in the force of gravity was then added, and afterward a special correction derived from Whitney's table. It is stated by Whitney that the corrections assigned to the several months in his tables apply more especially to the middle days, and may be modified when the observations are made near either end. In these computations the tabulated values were applied without modification to the middle day only, and for the remaining days values were interpolated by the aid of the tabulated corrections for October and December, the preceding and following months.

After the completion of the calculations the error of each determination was deduced by subtracting from it the corresponding difference in altitude as determined by spirit level; and these errors have been tabulated for publication. In Table XIV the three columns of errors pertain in order to the determinations by Whitney's method with Summit as a base, by Whitney's method with Sacramento as a base, and by the new method. The plus sign indicates in each case that the corresponding determination made Colfax too high; the minus sign, too low.

In this series the average error by the new method is notably less than by either application of Whitney's.

III. The second edition of Whitney's treatise contains a series of practical examples illustrating the application of his tables and the advantage thereby accruing. Each illustration consists of a series of independent determinations of the altitude of a point visited by the field parties of the Californian Survey in 1870 or 1871. The computations were made first without the use of the tables and afterward with them, and each series of results was compared with its own mean for the purpose of ascertaining the harmony of its individual components among themselves. The publication does not include the data of observation, but Professor Whitney has kindly permitted me to copy a portion of them, and I have thus been enabled to repeat by the new method some of the computations. My work covers only six of his twenty-four examples, but serves sufficiently well the purpose of comparison.

The barometric data and the several hypsometric results, with their errors, are exhibited in Table XV. The first two columns following the dates give for each locality the barometric readings (reduced to 32° F.) at the two points used as base stations in the new computations,

* "Practical Tables in Meteorology and Hypsometry, being the Appendix to the Paper on the Use of the Barometer," p. 111.

TABLE XIV.

Determinations of Altitude of Colfax, Cal., from Single Observations made in November, 1870. Comparison of Errors by Different Methods of Computation.

Day.	Hour.	By Whitney's Method, the base station being— Summit.	By Whitney's Method, the base station being— Sacramento.	By New Method from Summit and Sacramento.
		Feet.	*Feet.*	*Feet.*
1	7 a. m	+ 57	+ 13	+ 35
	2 p. m	+ 1	+ 53	+ 15
	9 p. m	+ 5	+ 41	+ 15
2	7 a. m	− 4	+ 72	+ 29
	2 p. m	+ 5	+ 78	+ 37
	9 p. m	− 91	+ 48	− 6
3	7 a. m	− 50	+ 27	+ 4
	2 p. m	− 18	+ 18	− 4
	9 p. m	− 12	+ 38	+ 8
4	2 p. m	− 49	+ 33	− 13
	9 p. m	− 95	+ 47	− 18
5	7 a. m	− 99	+ 55	0
	2 p. m	− 93	+ 25	− 28
	9 p. m	− 87	+ 51	− 3
6	7 a. m	− 166	+ 51	− 17
	2 p. m	+ 6	+ 3	− 23
	9 p. m	− 154	+ 13	− 60
7	7 a. m	− 161	+ 58	− 21
	2 p. m	+ 5	+ 1	− 16
	9 p. m	− 103	+ 30	− 29
8	7 a. m	+ 17	+ 29	+ 6
	2 p. m	− 5	− 9	− 13
	9 p. m	− 29	+ 61	+ 38
9	7 a. m	− 101	+ 24	− 8
	2 p. m	− 9	+ 18	− 15
	9 p. m	− 67	+ 47	+ 9
10	7 a. m	+ 102	+ 8	+ 38
	9 p. m	+ 8	+ 20	+ 12
11	7 a. m	− 38	+ 4	+ 14
	2 p. m	+ 32	+ 40	+ 35
	9 p. m	− 4	+ 37	+ 23
12	7 a. m	+ 19	+ 23	+ 32
	2 p. m	+ 31	+ 50	+ 36
	9 p. m	+ 42	+ 51	+ 43
13	7 a. m	+ 51	+ 12	+ 50
	2 p. m	+ 116	+ 24	+ 53
	9 p. m	+ 162	+ 75	+ 114
14	7 a. m	+ 236	+ 140	+ 204
	2 p. m	+ 199	+ 90	+ 118
	9 p. m	+ 96	− 4	+ 36
15	7 a. m	+ 61	− 14	+ 28
	2 p. m	+ 41	+ 25	+ 31
	9 p. m	+ 39	+ 18	+ 18
16	7 a. m	+ 9	− 36	+ 2
	2 p. m	+ 1	+ 50	+ 27
16	9 p. m	+ 40	+ 3	+ 17
17	2 p. m	+ 23	+ 39	+ 29
	9 p. m	+ 50	0	+ 23
18	7 a. m	− 1	− 9	+ 15
	2 p. m	+ 56	− 24	− 2
	9 p. m	+ 121	+ 13	+ 40
19	7 a. m	+ 85	+ 13	+ 59
	9 p. m	+ 51	+ 20	+ 31
20	7 a. m	+ 4	0	+ 14
	2 p. m	+ 66	+ 18	+ 19
	9 p. m	+ 59	− 4	+ 18
21	7 a. m	+ 49	− 32	+ 15
	2 p. m	+ 85	+ 51	+ 46
	9 p. m	+ 67	+ 8	+ 37
22	7 a. m	+ 92	− 40	+ 31
	2 p. m	+ 30	+ 38	+ 34
	9 p. m	+ 21	− 58	− 22
23	7 a. m	+ 43	− 21	+ 24
	2 p. m	− 14	− 85	+ 60
	9 p. m	+ 25	+ 6	+ 11
24	7 a. m	+ 13	0	+ 16
	2 p. m	− 11	+ 22	+ 3
	9 p. m	+ 34	+ 7	+ 8
25	7 a. m	+ 17	+ 3	+ 21
	2 p. m	+ 32	+ 91	+ 68
	9 p. m	− 52	+ 12	− 7
26	7 a. m	− 184	+ 17	− 21
	2 p. m	− 36	+ 37	− 9
	9 p. m	− 106	+ 87	+ 8
27	7 a. m	− 89	+ 59	+ 28
	2 p. m	+ 32	+ 51	+ 20
	9 p. m	− 23	+ 22	− 16
28	7 a. m	+ 20	+ 10	+ 14
	2 p. m	+ 11	+ 35	+ 8
	9 p. m	− 63	+ 49	+ 7
29	7 a. m	− 106	+ 43	− 4
	2 p. m	+ 40	− 71	− 48
	9 p. m	− 97	+ 10	− 32
30	7 a. m	− 107	+ 33	− 17
	2 p. m	0	+ 15	+ 7
	9 p. m	− 10	+ 48	+ 22
	Mean	55.9	33.2	26.9
	Range	402	225	264

TABLE XV.

Altitude Determinations in California, from Observations by the Geological Survey of California in 1870.

1.—ALTITUDE OF GOLD RUN ABOVE COLFAX.

Day.	Hour.	Barometer Reading.			Altitude by—		Residual by—	
		Summit.	Colfax.	Gold Run.	Whitney.	New Method.	Whitney.	New Method.
		Inches.	*Inches.*	*Inches.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*
Oct. 7	7 a. m.	23.383	27.494	26.765	804.2	767.5	− 5.3	−14.0
	2 p. m.	.410	.487	.745	814.3	788.7	+ 4.8	+ 7.2
	9 p. m.	.418	.499	.764	802.5	780.3	− 7.0	− 1.2
8	7 a. m.	.409	.520	.775	812.6	784.5	+ 3.1	+ 3.0
9	2 p. m.	.311	.341	.597	820.5	800.1	+11.0	+18.6
	9 p. m.	.251	.340	.611	804.3	772.0	− 5.2	− 9.5
10	7 a. m.	.245	.370	.631	807.9	774.6	− 1.6	− 6.9
	2 p. m.	.227	.371	.624	813.9	779.8	+ 4.4	− 1.7
11	7 a. m.	.257	.445	.690	812.3	778.9	+ 2.8	− 2.6
	3.30 p. m.	.262	.458	.690	819.7	791.0	+10.2	+ 9.5
	9 p. m.	.316	.460	.725	792.7	766.8	−16.8	−14.7
12	7 a. m.	.346	.488	.736	816.1	785.1	+ 6.6	+ 3.6
	2 p. m.	.364	.493	.740	812.7	789.2	+ 3.2	+ 7.7
	9 p. m.	.386	.512	.768	801.4	779.9	− 8.1	− 1.6
13	7 a. m.	.424	.556	.805	796.7	786.5	−12.8	+ 5.0
	2 p. m.	.388	.514	.768	809.6	781.9	+ 0.1	+ 0.4
	9 p. m.	.396	.523	.781	803.9	778.1	− 5.6	− 3.4
Mean					809.5	781.5	6.4	6.5
Range							27.8	33.3

2.—ALTITUDE OF YOU BET ABOVE COLFAX.

Day.	Hour.	Barometer Reading.			Altitude by—		Residual by—	
		Summit.	Colfax.	You Bet.	Whitney.	New Method.	Whitney.	New Method.
		Inches.	*Inches.*	*Inches.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*
Nov. 10	9 p. m.	23.323	27.641	27.080	585.3	558.2	+27.2	+12.2
11	7 a. m.	.318	.639	.086	564.5	550.2	+ 6.4	+ 4.2
	1.45 p. m.	.326	.601	.053	572.5	550.8	+14.4	+ 4.8
	7.25 p. m.	.323	.589	.041	568.3	553.0	+10.2	+ 7.0
12	7 a. m.	.299	.570	26.997	597.9	577.1	+39.8	+31.1
16	2 p. m.	.374	.576	27.046	562.2	543.3	+ 4.1	− 2.7
	9 p. m.	.416	.611	.095	540.6	529.7	−17.5	−16.3
17	1 p. m.	.474	.673	.148	552.8	538.7	− 5.3	− 7.3
18	2 p. m.	.591	.789	.260	550.8	542.7	− 7.3	− 3.3
20	7 a. m.	.473	.731	.188	557.6	549.0	− 0.5	+ 3.0
	2 p. m.	.513	.708	.187	544.5	535.5	−13.6	−10.5
	9 p. m.	.536	.734	.211	542.8	536.9	−15.3	− 9.1
21	7.30 a. m.	.555	.796	.263	549.3	541.3	− 8.8	− 4.7
	2 p. m.	.534	.720	.187	557.9	548.7	− 0.2	+ 2.7
	9 p. m.	.542	.707	.185	540.6	540.3	−17.5	− 5.7
22	7 a. m.	.516	.691	.170	539.9	537.9	−18.2	− 8.1
23	7 a. m.	.434	.652	.125	549.9	538.2	− 8.2	− 7.8
Dec. 8	2 p. m.	.246	.738	.169	563.2	543.3	+ 5.1	− 2.7
	9 p. m.	.293	.729	.165	564.0	545.3	+ 5.9	− 0.7
9	7 a. m.	.329	.659	.109	553.1	546.4	− 5.0	+ 0.4
12	7 a. m.	.148	.512	26.954	557.9	548.9	− 0.2	+ 2.9
	7 p. m.	.171	.553	.985	551.7	556.5	− 6.4	+10.5
Mean					558.1	546.0	10.8	7.2
Range							58.0	47.4

TABLE XV—Continued.

3.—DISTANCE OF CAMP 9 BELOW COLFAX.

Day.	Hour.	Barometer Reading.			Altitude by—		Residual by—	
		Summit.	Colfax.	Camp 9.	Whitney.	New Method.	Whitney.	New Method.
		Inches.	*Inches.*	*Inches.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*
Sept. 21	9 p. m.	23.397	27.486	28.862	1,369.6	1,398	—13.4	—14
22	7 a. m.	.353	.471	.854	1,361.4	1,406	—21.6	— 6
23	7 a. m.	.277	.452	.897	1,412.7	1,445	+29.7	+33
	2 p. m.	.269	.445	.850	1,397.2	1,406	+14.2	— 6
	9 p. m.	.298	.466	.871	1,381.9	1,408	— 1.1	— 4
24	7 a. m.	.320	.518	.945	1,384.6	1,425	+ 1.6	+13
	2 p. m.	.298	.481	.854	1,363.6	1,372	—19.4	—40
	9 p. m.	.337	.483	.886	1,382.3	1,415	— 0.7	+ 3
25	7 a. m.	.350	.525	.940	1,381.6	1,416	— 1.4	+ 4
26	7 a. m.	.315	.474	.869	1,370.2	1,402	—12.8	—10
	9 p. m.	.325	.493	.925	1,407.7	1,435	+24.7	+23
Mean					1,383.0	1,411.6	12.8	14.2
Range							51.3	73

4.—ALTITUDE OF LAKEPORT ABOVE SACRAMENTO.

Day.	Hour.	Barometer Reading.			Altitude by—		Residual by—	
		Colfax.	Sacramento.	Lakeport.	Whitney.	New Method.	Whitney.	New Method.
		Inches.	*Inches.*	*Inches.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*
Oct. 19	7 a. m.	27.735	30.212	28.840	1,269.7	1,306	—55.8	— 7
	2 p. m.	.633	.149	.760	1,323.2	1,301	— 2.3	—12
	9 p. m.	.681	.121	.799	1,250.7	1,278	—74.8	—35
20	7 a. m.	.635	.115	.758	1,259.7	1,289	—65.8	—24
	2 p. m.	.571	.044	.646	1,339.1	1,334	+13.6	+21
	9 p. m.	.542	29.987	.641	1,269.1	1,298	—56.4	—15
21	2 p. m.	.409	.906	.488	1,355.7	1,340	+30.2	+27
	9 p. m.	.365	.871	.467	1,342.1	1,321	+16.6	+ 8
22	7 a. m.	.311	.834	.432	1,339.7	1,309	+14.2	— 4
	2 p. m.	.303	.847	.389	1,355.1	1,352	+29.6	+39
23	7 a. m.	.297	.825	.384	1,357.0	1,345	+31.5	+32
	2 p. m.	.281	.882	.426	1,302.7	1,298	—22.8	—15
	9 p. m.	.246	.813	.424	1,307.3	1,274	—18.2	—39
24	7 a. m.	.245	.798	.424	1,287.2	1,268	—38.3	—45
	2 p. m.	.278	.859	.395	1,382.6	1,338	+57.1	+25
	9 p. m.	.280	.915	.467	1,367.0	1,293	+41.5	—20
25	7 a. m.	.369	.906	.475	1,337.4	1,330	+11.9	+17
	2 p. m.	.344	.879	.415	1,370.8	1,362	+45.3	+49
	9 p. m.	.358	.889	.474	1,346.4	1,317	+20.9	+ 4
26	7 a. m.	.225	.781	.388	1,320.6	1,318	— 4.9	+ 5
	2 p. m.	.312	.860	.430	1,324.5	1,322	— 1.0	+ 9
	9 p. m.	.396	30.010	.552	1,357.7	1,332	+32.2	+19
27	7 a. m.	.508	.078	.684	1,305.4	1,276	—20.1	—37
	2 p. m.	.567	.167	.685	1,375.6	1,345	+50.1	+32
	9 p. m.	.635	.172	.785	1,290.9	1,287	—34.6	—26
Mean					1,325.5	1,313	31.6	22.6
Range							131.9	94

TABLE XV—Continued.

5.—DISTANCE OF GEYSER SPRINGS BELOW COLFAX.

Day.	Hour.	Barometer Reading.			Altitude by—		Residual by—	
		Summit.	Colfax.	Geyser Springs.	Whitney.	New Method.	Whitney.	New Method.
		Inches.	*Inches.*	*Inches.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*
Sept. 15	9 p. m........ ..	23.215	27.398	28.398	993.0	1,004.3	+ 9.6	+ 5.0
16	7 a. m............	.216	.430	.439	985.7	1,004.6	+ 2.3	+ 5.3
17	7 a. m............	.226	.444	.437	970.7	988.0	—12.7	—11.3
	9 p. m............	.277	.457	.452	984.1	1,000.5	+ 0.7	+ 1.2
Mean					983.4	999.3	6.3	5.7
Range					....	....	22.3	16.6

6.—DISTANCE OF LONG VALLEY BELOW COLFAX.

Day.	Hour.	Barometer Reading.			Altitude by—		Residual by—	
		Colfax.	Sacramento.	Long Valley.	Whitney.	New Method.	Whitney.	New Method.
		Inches.	*Inches.*	*Inches.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*
Nov. 8	7 a. m............	27.662	30.246	28.788	1,062.9	1,069	— 5.2	— 6
	2 p. m............	.622	.160	.717	1,034.0	1,057	—34.1	—18
9	2 p. m............	.461	.024	.539	1,022.6	1,033	—45.5	—42
	9 p. m	.512	.078	.679	1,106.9	1,115	+38.8	+40
13	7 a. m............	.536	.079	.684	1,091.9	1,107	+23.8	+32
	2 p. m............	.540	.053	.614	1,054.9	1,048	—13.2	—27
	9 p. m......	.517	.084	.662	1,103.7	1,094	+35.6	+19
Range					1,068.1	1,074.7	28.0	26.3
Mean					....	....	84.3	82.0

and the next gives the readings at the new station. The base station employed by Whitney is in each case a base station of the new method, and its locality is indicated by the title of the sub-table. The next two columns contain the altitudes determined by the two computations, and the final columns give the variations of the individual results from the means of their series. In the case of these six localities the barometric measurements are not checked by leveling, so that the only test of the methods is derived from the relative concordance of their results. Each determination was compared with the mean of its series and the difference was entered in the column of residuals.

The reader who compares this table with the corresponding tables on pages 99 to 109 of Whitney's treatise (second edition), will note certain discrepancies which need to be explained. It happened in several instances that the computations could not be made by the new method for certain hours for which Whitney had made them, by reason of the lack of observations at the second base station. Moreover, the writer was led by the internal evidence of the record to discard as erroneous certain observations at Colfax which had been retained in the earlier computa-

tions.* In each case the corresponding determinations by Whitney were omitted from the comparison. The changes wrought by these omissions were not prejudicial to his method, but on the contrary rendered his results more harmonious.

Four of the illustrative new stations are intermediate in altitude between the base stations to which they are referred; two, Camp 9 and Geyser Springs, are not. Four localities afford better results to the new method than to the old; two, Camp 9 and Gold Run, afford poorer. Upon the average, the residuals by the new method are 10 per cent smaller than by the old.

In Table XVI the results of the several comparisons are summarized. The second column indicates the points used as base stations in the several computations by Whitney's method, the indicated point being, in each case, one of the pair of bases employed in the corresponding computations by the new method. The second column shows the number of independent results compared. The fourth and fifth give for the two methods the average errors or residuals of the individual determinations. Where Colfax was the new station, each determination was compared with a result determined by spirit level, but in the other cases the standards were merely the means of individual determinations. The numbers in the last column were obtained by dividing those in the fifth by those in the fourth, and are the ratios of the errors incurred by the new method to the errors incurred by Whitney's. The footings show that in four hundred independent comparisons, falling into ten separate series, distinguished by locality or other conditions, the average error by the new method is 85 per cent of the average error by Whitney's method. Of the ten series, three exhibit ratios favorable to Whitney's method, and the remainder favor the new method. On the whole, the comparisons award the preference to the new method, but the preponderance is not great.

* The observer at Colfax, in September, 1870, appears to have been addicted to a mistake in the reading of the scale, which is frequently made by inexperienced barometric observers, and which produces an error in the record amounting to either the tenth or the twentieth of an inch. Pencil memoranda on the pages of the records loaned to me indicated that some mistakes of this sort had already been detected, but others were not marked. If the purpose of the computations had been the determination of the altitude merely, it would have been proper to assign the *probable* correction to those readings and use them, but for the actual purpose rejection seemed the only legitimate course.

Whitney states that while the majority of his tests exhibit a gain by the use of his tables, there are a few which show a loss. Two of these adverse examples he publishes (p. 109), and one of them—the determination of Geyser Springs—involves, as I believe, two errors by the Colfax observer. If the bad observations be rejected, or if they be assigned the highly probable correction of —0.05 inch, the unfavorable example is converted into a favorable one.

The writer has been accustomed for several years, in the supervision of barometric work, to employ a check which effectually eliminates errors of this class. The portable barometer of Green, the instrument used by all American surveys, has two verniers, inseparably attached to each other but moving over different parts of the scale. The upper one is used at low altitudes, the lower at high. The check is obtained by requiring the observer, after adjusting the proper vernier to the surface of the mercury, to read and record *both* verniers. The difference between the two readings is for each instrument a constant quantity, and each reading therefore checks the accuracy of the other.

TABLE XVI.

Summary of Errors of Altitude Determinations by Whitney's Method and by the New Method; derived from Tables XII, XIV, and XV.

New Station and Character of Data.	Whitney's Base Station.	Number of Results	Average Errors by— Whitney.	Average Errors by— New.	Ratio.
			Feet.	*Feet.*	
Colfax; triple means for twenty-four months	Sacramento	72	10.8	11.6	1.07
Colfax; triple means for twenty-four months	Summit	72	15.2	11.6	.76
Colfax; single observations in November, 1870	Sacramento	86	33.2	26.9	.81
Colfax; single observations in November, 1870	Summit	86	55.9	26.9	.48
Gold Run; single observations	Colfax	17	6.4	6.5	1.02
You Bet; single observations	do	22	10.8	7.2	.67
Camp 9; single observations	do	11	12.8	14.2	1.11
Lakeport; single observations	Sacramento	25	31.6	22.6	.71
Geyser Springs; single observations	Colfax	4	6.3	5.7	.90
Long Valley; single observations	do	7	28.0	26.3	.94
Total		402	Mean		.85

The computations were made and the tables were prepared for the purpose of comparing the *variations* in the results obtained by the two systems, these variations affording the best practicable measure of their relative precision. They serve another purpose, however, for they also show the relations between the mean altitudes determined by the two methods. In the determinations of Colfax there are no discrepancies, for these are based upon the very observations which served, on the one hand, to construct Whitney's table of corrections, and, on the other, to determine the constant of the new formula, and the application of the corrections and the formula could not fail to give *average* results in harmony with the original data and with each other; but when the methods are applied to other points, their determinations are found to exhibit constant differences. The altitudes given in Table XV are in each case differences in level between the indicated new station and the indicated base, the new station being in some cases higher than the base, and in other cases lower. In three of the six instances the mean difference in level determined by the new method is greater than the corresponding determination by the old, and in the remaining three it is less. If, however, we compare the altitudes of the new stations when referred to the sea level, or to any other uniform standard, we find that the divergence between the two series of results is always in the same direction.

This fact is exhibited in Table XVII, where each new station is referred to Colfax, the plus sign indicating that it is higher than Colfax, the minus sign that it is lower. The stations are arranged on the page in the order of their altitudes,—from Gold Run, 800 feet above Colfax, to Camp 9, 1,400 feet below. The figures in the right-hand column were obtained by subtracting the altitudes given by the new method from

the corresponding altitudes obtained by Whitney, and show that in every case Whitney's method gives a higher determination to the new station than does the new. In the absence of determinations of the several points by level, it is impossible to lay the discrepancy to the fault of one method rather than the other, and the conditions of the computations, which were somewhat varied, throw no light upon the subject.

TABLE XVII.

Comparison of Californian Altitudes, computed by Whitney and by the New Method.

New Station.	Base Stations.		Month.	Altitude above Colfax.		(I) minus (II).
	Whitney.	New Method.		Whitney (I).	New (II).	
				Feet.	*Feet.*	*Feet.*
Gold Run	Colfax	Colfax and Summit	October	+ 809	+ 781	+28
You Bet	do	do	November	+ 558	+ 546	+12
Geyser Springs	do	do	September	− 983	− 999	+16
Long Valley	do	Sacramento and Colfax	November	−1,068	−1,075	+ 7
Lakeport	Sacramento	do	October	−1,074	−1,086	+12
Camp 9	Colfax	Colfax and Summit	September	−1,383	−1,412	+29

The observations were made in three different months of the year 1870. In Whitney's computations Colfax was used as the base station in five cases and Sacramento in one: in three cases the new station was higher than the base, and in the remaining three it was lower. In the computations by the new method Colfax and Summit were the bases for four localities, and Sacramento and Colfax for the remaining two: in four cases the new station was intermediate in altitude between the bases; in the remaining two it fell below the lower base. The divergence of result is thus shown to be independent of the time of year and of the selection of base stations, retaining its character whether the base station for the old method lay above or below the new station, and whether the base stations for the new method included or excluded the new station.

It is not easy to see how a constant error, such as is here indicated, could be introduced by either hypsometric method. The corrections by each system are determined empirically from observations made in the very region where they are applied. Any change which might be made in the constant of the new formula would increase the discrepancies in some cases and diminish them in others, and no possible value could be assigned to it which would produce harmony in the results. The only competent explanation which occurs to the writer is *a priori* highly improbable. If the determination by the railroad surveyors of the vertical interspaces between the stations at Sacramento, Colfax, and Summit is grossly in error, and in such way that the estimated altitude of

Colfax is relatively 25 or 50 feet too low, the effect upon Whitney's determinations and those made by the new method would be such as to produce a divergence between them of the character and amount observed. It would be rash, however, to impugn the accuracy of the engineering work upon such grounds.

If all the altitudes published by Whitney were redetermined by the new method, it is quite possible that a satisfactory explanation would be reached; but lack of time forbids the pursuit of the subject, at least for the present.

Another relation of the two series of determinations is worthy of note, viz., their parallelism. An inspection of Tables XIV and XV, which exhibit the determinations from single sets of observations, shows that an exceptionally great error by one method usually corresponds to an exceptionally great error in the same direction by the other. In the former table there are 123 instances in which the errors incurred by the two methods have the same sign, and only 47 in which their signs are different. In the latter table the signs show 73 correspondences and only 18 discrepancies. The same relation appears when the series of results are plotted in the form of curves. In the case of each station the curves representing the errors by the two methods approach more nearly to parallelism than either of them approaches to coincidence with its mean line.

This relation does not hold good with the results contained in Table XII, which are based on monthly means; the correspondences of sign barely exceed in number the differences.

The proper interpretation of these peculiarities appears to be, first, that the devices employed in the two computations to eliminate error have been efficacious in the case of the same classes of error, and have agreed likewise as to the errors they have failed to reach; and, second, that the latter class of errors are partially eliminated by the use of monthly means. When we take into consideration the nature of the various possible sources of error, and the character of the corrective expedients employed by the two methods, it becomes evident that the chief error they both fail to eliminate from the determinations from single sets of observations is that of non-periodic gradient, and that the error with which they most successfully cope is the one arising from the diurnal variation of the density of air, due chiefly to temperature. The actual difference between the degrees of accuracy attained by the two methods may be taken, therefore, with some degree of confidence, to represent the difference in their success in eliminating errors due to temperature, and we are permitted to assume that the small residual temperature errors are masked in these results by the concurrent gradient errors. If the comparison could be repeated under such conditions that errors of gradient would not largely enter, it is probable that the slight actual advantage shown by the new method would be found to assume a relatively great importance.

COMPARISON WITH PLANTAMOUR'S METHOD.

Plantamour's hypsometric method resembles Whitney's in that it includes a table of corrections based upon a long series of observations; but the corrections are applied to the temperature observations and not to the altitudes, and there are other and important differences. The groundwork of his tables consists of eighteen years' continuous meteorologic observations at Geneva and the Great St. Bernard—a series of observations which his discussions have rendered classic, and which have made the most notable contributions alike to hypsometry and to meteorology. The Geneva Observatory is situated in a valley at the base of the Alps, and the Inn of St. Bernard stands high up in the mountains, with a great spur of Mont Blanc between. Their horizontal disance is 55 miles; their difference in altitude 2,070.3 meters, or about 6,792 feet.

For different months of the year and hours of the day Professor Plantamour computed the height of St. Bernard above Geneva from the means of the eighteen years' observations, making use not only of the barometric determinations of pressure and the thermometric determinations of temperature but also of the psychrometric determinations of humidity. He then compared each of these results with the actual altitude as determined by spirit level, and deduced from the comparison the correction necessary to be applied to the sum of the observed temperatures in order to eliminate the error. These corrections he embodied in a table which appears in the second part of Volume XVI of the Memoirs of the Geneva Society of Physics and Natural History. The table does not cover the entire year, but only the warmer months and the daylight hours, to which observations for the determination of altitude are usually restricted in the Alps. In the same place he describes his method of applying it, and publishes an extended series of illustrative examples, in each of which the new station was within or near the Alps, and either Geneva or St. Bernard was used as the base station. A separate computation was made for each observation at each new station, and the data and results are given in full, so that his method is completely exemplified. His procedure with each group of synchronous observations was as follows:

The barometer reading at the new station was first compared with the reading at Geneva, and an approximate difference of altitude was deduced in the usual manner. To this approximate altitude corrections for temperature, moisture, and gravitation were applied in the customary way, except that corrected temperatures at the two stations were substituted for the observed temperatures. The manner of correcting the temperatures was peculiar and needs to be given in detail. Since dense air acquires heat from the ground more rapidly than rare air, he ascribed a greater local variation to temperature at Geneva than at

St. Bernard, and assigned it a larger measure of correction. The tabulated correction is a correction to the sum of the two temperatures, and two-thirds of this correction was assigned to the Geneva temperature, leaving the remaining third to be applied to that observed at St. Bernard. Correspondingly, the temperature observed at the new station was increased or diminished by two-thirds of the tabulated correction if the station lay in the vicinity of Geneva, and by one-third of the tabulated correction if its altitude was nearly the same as that of St. Bernard. If its position was midway it received the half of the total correction, and if it had an altitude greatly in excess of that of St. Bernard the correction applied was less than one-third, or even in some cases nothing.

The difference in altitude of the new station and Geneva having been thus computed, a similar computation was made of the difference in altitude of the new station and St. Bernard, and in the final result these two determinations were given weights according to the vertical position of the new station, the determination by means of the nearer base station being considered the more trustworthy.

Where two or more observations were made at any new station, care was taken to assign to the result from each one a weight dependent upon the atmospheric conditions at the time the observation was made. For this purpose a computation of the altitude of St. Bernard above Geneva was made from the observations at the same hour, and from this was deduced the amount of change which would need to be made in the sum of the observed temperatures at these places in order to correct the error of the determined altitude. This temperature correction was then compared with the temperature correction of the table for the hour and month, and consideration was given to the force and direction of the wind and to the cloudiness or clearness of the sky. Since the tabulated correction was derived from the mean of many days, or from the average day, it must evidently be inapplicable to days which differ from the average standard. For clear and still days it is too small; for cloudy or very windy days it is too large; and an inspection of the recorded weather at the time of observation enables the computer to judge whether the temperature correction necessary to deduce the true altitude differs from the tabulated correction in a way that can be accounted for by the local conditions of sky and wind. If it can be so accounted for, there is presumptive evidence that the general condition of the air column between Geneva and St. Bernard is one of equilibrium, and that the altitude of the new station deduced at that time is entitled to receive a large weight. If it cannot be thus accounted for, then a gradient must be supposed to exist between those points, and the deduced altitude of the new station has less value. In assigning it a weight, Plantamour gave consideration, first, to the amount of gradient as indicated by the temperature corrections, and, second, to the geo-

graphic position of the station with reference to the two bases,—a matter in which the judgment of the computer was brought into play, and to which a knowledge of the geography and climate of the country was an important adjunct.

It will be seen that this barometric system is absolutely dependent upon a long preliminary series of observations at the pair of stations to be afterward used as bases. It is as strictly a local system as Professor Whitney's, and while in the skillful hands of Plantamour it undoubtedly afforded results of a high degree of accuracy, it demands in its use the application of so much knowledge and acumen that it can hardly be intrusted to the ordinary computer.

The series of examples published by Plantamour includes thirty-nine new stations, at some of which the barometer was read once only, but at most of which it was read from two to twenty-two times. For the purpose of comparative computation, a selection was made by the writer of the six stations which gave opportunity for the greatest number of individual comparisons, and the altitudes of these stations were computed by the new method, a separate result being obtained for each observation. From these separate results a weighted mean for the altitude of each station was derived, the weights being determined simply by the wind factor. Since the winds which accompany cyclonic movements of the atmosphere are approximately proportional in force to the gradients with which they are associated, gradient errors are liable to be greater during the existence of a high wind. The horizontal distances between the base stations and new stations under consideration are so great that the accuracy of the determinations is liable to be seriously impaired by high gradients. The winds are indicated in the record of observations by a notation which calls a calm 0 and a high wind 3. In the deduction of the means, all the results obtained when the strongest wind at either station was 1 were ascribed a weight of unity. Results affected by a wind with the force 2 or 3 were ascribed weights of one-half or one-third respectively.

In Table XVIII the first column gives the new stations and indicates the days and hours at which the observations were made. The second column shows for each hour the altitude of the station above the sea, expressed in meters, as deduced by the new method. The third column gives the remainders obtained by subtracting the weighted mean altitude for each station from the individual determinations. The fourth and fifth columns contain Plantamour's determinations of the same altitudes at the same hours from the two bases taken separately, Geneva being the base for all determinations in the fourth column and St. Bernard for all in the fifth. The numbers of the sixth and seventh columns were obtained by subtracting from the numbers of the fourth and fifth their respective weighted means.

TABLE XVIII.

Altitude Determinations in the Alps, from Observations published by Prof. E. Plantamour. (All Altitudes are referred to Sea Level.)

Place and Time of Observation.	Altitude by New Method.	Deviation from Weighted Mean.	Altitude by Plantamour, the Base Station being—		Deviation from Weighted Mean.	
			Geneva.	St. Bernard.	Geneva.	St. Bernard.
EVOLÈNA.						
1859.	*Meters.*	*Meters.*	*Meters.*	*Meters.*	*Meters.*	*Meters.*
Sept. 1—2 p. m	1,380.1	+6.3	1,398.0	1,378.2	+19.4	−5.4
1—4 p. m	1,385.0	+11.2	1,402.3	1,381.9	+23.7	+3.3
1—6 p. m	1,374.8	+1.0	1,389.7	1,376.6	+11.1	−2.0
1—8 p. m	1,366.1	−7.7	1,377.2	1,370.5	−1.4	−8.1
2—6 a. m	1,367.4	−6.4	1,385.0	1,357.0	+6.4	−21.6
2—8 p. m	1,371.1	−2.7	1,382.9	1,367.4	+4.3	−11.2
3—6 a. m	1,372.4	−1.4	1,379.5	1,378.5	+0.9	−0.1
Weighted Mean	1,373.8	5.2	1,378.6		9.6	7.4
Range	....	18.9	....	....	24.5	24.9
HOSPICE DE LA GRIMSEL.						
1858.						
July 31— 8 p. m	1,862.5	−13.6	1,869.1	1,868.0	−8.2	−9.3
31—10 p. m	1,867.0	−9.1	1,875.7	1,870.4	−1.6	−6.9
1859.						
Sept. 7—7 p. m	1,876.3	+0.2	1,883.5	1,879.2	+6.2	+1.9
7—8 p. m	1,878.8	+2.7	1,880.3	1,882.3	+3.0	+5.0
7—9 p. m	1,880.5	+4.4	1,882.2	1,883.2	+4.5	+5.9
8—6 a. m	1,877.3	+1.2	1,871.2	1,877.6	−6.1	+0.3
8—6 p. m	1,873.3	−2.8	1,882.6	1,874.9	+5.3	−2.4
8—8 p. m	1,877.9	+1.8	1,888.4	1,880.5	+11.1	+3.2
9—6 a. m	1,876.1	0.0	1,879.5	1,875.2	+2.2	−2.1
Weighted Mean	1,876.1	4.0	1,877.3		5.4	4.1
Range	....	18.0	....	....	19.3	15.2
SERRAVAL.						
1852.						
July 27— 9 p. m	833.3	−3.6	841.2	....	+1.0	....
27—10 p. m	835.3	−1.6	842.5	....	+2.3	....
28— 7 a. m	840.0	+3.1	846.4	....	+6.2	....
28— 8 a. m	841.9	+5.0	847.4	....	+7.2	....
28— 2 p. m	836.6	−0.3	841.8	....	+1.6	....
28— 7 p. m	826.7	−10.2	830.5	....	−9.7	....
28— 8 p. m	827.1	−9.8	831.5	....	−8.7	....
28— 9 p. m	830.2	−6.7	834.9	....	−5.3	....
28—10 p. m	831.9	−5.0	838.8	....	−1.4	....
29— 8 a. m	836.0	−0.9	838.9	....	−1.3	....
29—10 a. m	836.3	−0.6	841.6	....	+1.4	....
29—12 m.	836.4	−0.5	840.4	....	+0.2	....
29— 6 p. m	825.2	−11.7	825.6	....	−14.6	....
29— 8 p. m	832.5	−4.4	834.1	....	−6.1	....
29—10 p. m	832.8	−4.1	834.7	....	−5.5	....
30— 6 a. m	834.0	−2.9	837.4	....	−2.8	....
1853.						
Aug. 19—12 m	850.3	+13.4	848.4	....	+8.2	....
19— 2 p. m	844.0	+7.1	842.8	....	+2.6	....
19— 3 p. m	842.3	+5.4	841.6	....	+1.4	....

TABLE XVIII—Continued.

Place and Time of Observation.	Altitude by New Method.	Deviation from Weighted Mean.	Altitude by Plantamour, the Base Station being—		Deviation from Weighted Mean.	
			Geneva.	St. Bernard.	Geneva.	St. Bernard.
SERRAVAL—Continued.						
1853.	*Meters.*	*Meters.*	*Meters.*	*Meters.*	*Meters.*	*Meters.*
20— 8 p. m..........	835. 6	— 1. 3	831. 3	....	— 8 9	....
21— 8 a. m	845. 1	+ 8. 2	845. 9	....	+ 5. 7	....
21—12 m............	847. 8	+10. 9	846. 2	....	+ 6. 0	....
Weighted Mean	836. 9	5. 3	840. 2	....	4. 9	....
Range	....	25. 1	....	....	22. 8	....
CHAMOUNIX.						
1857.						
July 2— 8 a. m	1, 039. 4	— 0. 5	1, 045. 4	1, 041. 0	+ 1. 3	— 3. 1
2—12 m..............	1, 043. 8	+ 3. 9	1, 051. 6	1, 040. 3	+ 7. 5	— 3. 8
2— 2 p. m............	1, 040. 2	+ 0. 3	1, 046. 4	1, 042. 9	+ 2. 3	— 1. 2
2— 4 p. m............	1, 037. 8	— 2. 1	1, 041. 6	1, 050. 8	— 2. 5	+ 6. 7
2— 9 p. m............	1, 036. 3	— 3. 6	1, 044. 0	1, 034. 3	— 0. 1	— 9. 8
3— 6 a. m	1, 038. 1	— 1. 8	1, 048. 7	1, 029. 4	+ 4. 6	—14. 7
3—10 a. m............	1, 042. 3	+ 2. 4	1, 053. 1	1, 038. 7	+ 9. 0	— 5. 4
3— 9 p. m............	1, 036. 3	— 3. 6	1, 039. 2	1, 046. 2	— 4. 9	+ 2. 1
4— 6 a. m............	1, 042. 3	+ 2. 4	1, 039. 5	1, 051. 5	— 4. 6	+ 7. 4
4— 4 p. m............	1, 043. 7	+ 3. 8	1, 048. 1	1, 041. 5	+ 4. 0	— 2. 6
4—10 p. m............	1, 039. 0	— 0. 9	1, 035. 8	1, 052. 5	— 8. 3	+ 8. 4
Weighted Mean	1, 039. 9	1. 4	1, 044. 1		4. 5	5. 9
Range	....	7. 5	....	....	15. 8	23. 1
BOURG ST. PIERRE.						
1855.						
July 28— 6 p. m..........	1, 636. 2	— 2. 6	1, 650. 5	1, 635. 8	+10. 4	— 4. 8
28— 8 p. m...........	1, 635. 2	— 3. 6	1, 644. 5	1, 136. 8	+ 4. 4	— 3. 3
29— 6 a. m...........	1, 635. 8	— 3. 0	1, 644. 8	1, 636. 5	+ 4. 7	— 3. 6
29—10 a. m..........	1, 637. 2	— 1. 6	1, 644. 8	1, 635. 4	+ 4. 7	— 4. 7
29— 6 p. m...........	1, 636. 8	— 2. 0	1, 636. 3	1, 642. 3	— 3. 8	+ 2. 2
29— 8 p. m...........	1, 638. 2	— 0. 6	1, 641. 8	1, 641. 0	+ 1. 7	+ 0. 9
30— 6 a. m...........	1, 635. 9	— 2. 9	1, 639. 4	1, 639. 2	— 0. 7	— 0. 9
30— 8 a. m...........	1, 639. 6	+ 0. 8	1, 646. 6	1, 639. 4	+ 6. 5	— 0. 7
30— 2 p. m...........	1, 644. 9	+ 6. 1	1, 661. 5	1, 639. 6	+21. 4	— 0. 5
30— 8 p. m...........	1, 636. 5	— 2. 3	1, 639. 6	1, 644. 3	— 0. 5	+ 4. 2
31— 6 a. m...........	1, 640. 4	+ 1. 6	1, 639. 9	1, 643. 0	— 0. 2	+ 2. 9
31— 8 a. m...........	1, 642. 4	+ 3. 6	1, 637. 4	1, 640. 5	— 2. 7	+ 0. 4
Aug. 5— 6 p. m....... ..	1, 633. 7	— 5. 1	1, 648. 8	1, 635. 5	+ 8. 7	— 4. 6
5— 8 p. m...........	1, 629. 9	— 8. 9	1, 645. 6	1, 630. 6	+ 5. 5	— 9. 5
5—10 p. m	1, 632. 0	— 6. 8	1, 643. 5	1, 634. 7	+ 3. 4	— 5. 4
6— 8 a. m...........	1, 638. 3	— 0. 5	1, 634. 4	1, 647. 0	— 5. 7	+ 6. 9
6—10 a. m...........	1, 640. 4	+ 1. 6	1, 642. 6	1, 638. 3	+ 2. 5	— 1. 8
6—12 m..............	1, 643. 3	+ 4. 5	1, 646. 4	1, 639. 6	+ 6. 3	— 0. 5
6— 2 p. m...........	1, 641. 1	+ 2. 3	1, 648. 5	1, 635. 3	+ 8. 4	— 4. 8
7— 6 p. m...........	1, 639. 3	+ 0. 5	1, 648. 5	1, 640. 2	+ 8. 4	+ 0. 1
7— 8 p. m...........	1, 641. 9	+ 3. 1	1, 650. 3	1, 641. 9	+10. 2	+ 1. 8
8— 8 a. m...........	1, 643. 5	+ 4. 7	1, 653. 4	1, 640. 3	+13. 3	+ 0. 2
Weighted Mean......	1, 638. 8	3. 1	1, 640. 1		6. 1	2. 9
Range	....	15. 0	....	....	27. 1	16. 4

TABLE XVIII—Continued.

Place and Time of Observation.	Altitude by New Method.	Deviation from Weighted Mean.	Altitude by Plantamour, the Base Station being—		Deviation from Weighted Mean.	
			Geneva.	St. Bernard.	Geneva.	St. Bernard.
CANTINE DE PROZ. 1855.	*Meters.*	*Meters.*	*Meters.*	*Meters.*	*Meters.*	*Meters.*
July 31—10 a. m.	1,808.1	+ 1.9	1,805.1	1,806.6	− 3.8	− 2.3
31—12 m.	1,811.8	+ 5.5	1,806.4	1,810.9	− 2.5	+ 2.0
31— 2 p. m.	1,809.0	+ 2.8	1,806.3	1,810.4	− 2.6	+ 1.5
31— 6 p. m.	1,805.7	− 0.5	1,801.5	1,812.2	− 7.4	+ 3.3
31— 8 p. m.	1,803.5	− 2.7	1,799.2	1,808.9	− 9.7	0.0
Aug. 1— 6 a. m.	1,806.4	+ 0.2	1,791.3	1,812.7	−17.6	+ 3.8
1— 8 p. m.	1,799.4	− 6.8	1,788.2	1,808.5	−20.7	− 0.4
2— 6 a. m.	1,805.4	− 0.8	1,785.7	1,815.5	−23.2	+ 6.6
6— 4 p. m	1,806.9	+ 0.7	1,809.3	1,807.9	+ 0.4	− 1.0
6— 6 p. m.	1,807.7	+ 1.5	1,806.9	1,811.6	− 2.0	+ 2.7
6— 8 p. m.	1,805.0	− 1.2	1,797.3	1,809.6	−11.6	+ 0.7
Weighted Mean	1,806.2	2.2	1,808.9		9.2	2.2
Range		12.3			23.6	8.9

In this case, as in the case of Colonel Williamson's observations, there is no absolute standard of comparison. The individual determinations of each station by the new method are compared with their own weighted mean, and the individual determinations of each station by Plantamour's method are compared with the weighted mean deduced by him. It would be more satisfactory if it were possible to compare each determination of altitude with an independent determination made by more precise methods, but as this is impossible, the only practicable criterion of precision is the internal harmony of each series of results. This is shown in the table by the lines entitled "Mean" and "Range", where the average residual and the range of variation are exhibited.

In Table XIX the *mean residuals* shown by the preceding table to appertain to the determinations of the altitudes of the several stations, are brought together, and with them are conjoined the approximate heights of the air columns comprised between the new stations and the two bases. In the space assigned to Plantamour's results the first column exhibits the mean residuals of those determinations in which he used Geneva as a base station; the second column exhibits the corresponding means for the results obtained with the use of St. Bernard as a base station; and the third column shows the mean residuals resulting from the use of both stations, its numbers being the arithmetic means of the corresponding numbers in the first and second columns. It will be observed that each of the numbers of this third column is greater than the corresponding number of the final column, which shows the mean residuals by the new method, while of the eleven numbers in the preceding two columns there are only two which are less than the corresponding numbers in the column derived from the results by the new

method. That is to say, in eleven sets of comparative computations, two only show smaller variations by Plantamour's method. There is one which shows the same variation, and the remaining eight show greater variations. The general means at the bottom of the table give 5.7 meters as the average residual of the entire series of Plantamour's results given in Table XVIII, and 3.5 meters as the average residual of the corresponding series of results by the new method, and it is probable that the ratio of 3 to 5 may fairly be taken as indicative of the relative precision of the two methods.

TABLE XIX.

Summary of Altitude Determinations in the Alps, showing Average Variation of Results.

New Station.	Approximate Vertical Space between New Station and—		Number of Results.	Mean Residual.			
				By Plantamour, from—			By New Method.
	Geneva.	St. Bernard.		Geneva.	St. Bernard.	Geneva and St. Bernard.	
	Meters.	*Meters.*		*Meters.*	*Meters.*	*Meters.*	*Meters.*
Evoléna	970	1,100	7	9.6	7.4	8.5	5.2
Hospice de la Grimsel	1,470	600	9	5.4	4.1	4.7	4.0
Serraval	430	1,640	23	4.9	....	....	5.3
Chamounix	630	1,440	11	4.5	5.9	5.2	1.4
Bourg St. Pierre	1,230	840	22	6.1	2.9	4.5	3.1
Cantine de Proz	1,400	670	11	9.2	2.2	5.7	2.2
Mean	1,020	1,050	....	6.6	4.5	5.7	3.5

TABLE XX.

Summary of Altitude Determinations in the Alps, showing Range of Results.

New Station.	Vertical Space between New Station and—		Range of Variation of Computed Altitudes.			
			By Plantamour, from—			By New Method.
	Geneva.	St. Bernard.	Geneva.	St. Bernard.	Geneva and St. Bernard.	
	Meters.	*Meters.*	*Meters.*	*Meters.*	*Meters.*	*Meters.*
Evoléna	970	1,100	24.5	24.9	45.3	18.9
Hospital de la Grimsel	1,470	600	19.3	15.2	20.4	18.0
Serraval	430	1,640	22.8	....	....	25.1
Chamounix	630	1,440	15.8	23.1	23.7	7.5
Bourg St. Pierre	1,230	840	27.1	16.4	30.9	15.0
Cantine de Proz	1,400	670	23.6	8.9	29.8	12.3
Mean	1,020	1,050	22.2	17.7	30.0	16.1

Table XX gives a similar summary of the indications to be derived from the *range of variation* of the several series of determinations.

Here again the advantage appears to be with the new method, but less decidedly. Of the eleven cases of comparison there are three in which Plantamour's results exhibit a smaller range than their competitors, and eight in which their range is greater, while in the line of general means their ratio is approximately that of 4 to 5, the difference being in favor of the new method.

TABLE XXI.

Summary of Altitude Determinations in the Alps: Comparison of Computed Altitudes.

New Station.	Computed Height above Sea Level.				Excess of Plantamour's Results above those by New Method.		
	By Plantamour, from—			By New Method (weighted mean).			
	Geneva (mean).	St. Bernard (mean).	Geneva and St. Bernard (weighted mean).		Geneva.	St. Bernard.	Geneva and St. Bernard.
	(*A*)	(*B*)	(*C*)	(*D*)	(*A–D*)	(*B–D*)	(*C–D*)
	Meters.	*Meters.*	*Meters.*	*Meters.*	*Meters.*	*Meters.*	*Meters.*
Serraval	840.2	....	840.2	836.9	+ 3.3	....	+ 3.3
Chamounix	1,044.9	1,042.7	1,044.1	1,039.9	+ 5.0	+ 2.8	+ 4.2
Evoléna	1,387.8	1,372.1	1,378.6	1,373.8	+ 14.0	− 1.7	+ 4.8
St. Pierre	1,645.0	1,634.4	1,640.1	1,638.8	+ 6.2	− 4.4	+ 1.3
Pros	1,799.7	1,810.4	1,808.9	1,806.2	− 6.5	+ 4.2	+ 2.7
Grimsel	1,879.2	1,876.8	1,877.3	1,876.1	+ 3.1	+ 0.7	+ 1.2
Mean					+ 4.2	+ 0.3	+ 2.9

It is instructive to extend the comparison one step farther and place in juxtaposition the absolute determinations of altitude by the two methods. This is done in Table XXI, where for each station there are given, first, the mean of all Plantamour's determinations with Geneva as a base; second, the mean of all his determinations with St. Bernard as a base; third, Plantamour's weighted mean deduced from the discussion of all his determinations from both bases; and, fourth, the weighted mean deduced by the new method. In three additional columns a series of residuals are given, which were obtained by subtracting the mean altitude by the new method from the several means obtained by Plantamour's method. From these residuals it appears, first, that the determinations of height by the new method correspond on the average with Plantamour's determinations based upon St. Bernard, while they are decidedly smaller as a rule than Plantamour's determinations with Geneva as a base; second, that in every instance the determination by the new method falls below Plantamour's weighted mean, the average difference being about three meters. This latter result indicates some defect of a constant nature in one system or the other. If it is in Plantamour's, it probably lies in his somewhat arbitrary assumption that two-thirds of his temperature correction should be assigned to the lower station and one-third to the upper. If it pertains to the new method, it

undoubtedly inheres in the constant, the value of which has not yet been satisfactorily established. That value of the constant which would produce the best accord with Plantamour's results is 330,000 feet, being 160,000 feet less than the one provisionally adopted.

This test and the third of the series of tests derived from Whitney's observations are especially valuable because they involve that variety of station which must always be met in the actual use of any barometric method. The comparisons by means of Williamson's and Whitney's permanent stations are in danger of being vitiated by errors of local origin.

A further interest is given to the Alpine test by the fact that Plantamour distinctly recognizes the principle upon which the new method is based, but applies it in a different way. He even goes so far as to compute for each hour of observation at the new station the difference in altitude of the two base stations *for the purpose of ascertaining the condition of the intervening air column;* but instead of using this information directly, he endeavors to apply it indirectly by investigating the temperature and gradient. He attacks the problem in detail instead of in its totality, and the fact that his result is comparatively unsatisfactory is to be ascribed to the almost limitless complexity of the factors involved, eluding the analysis even of so skillful an investigator as the Genevan professor.

COMPARISONS BY MEANS OF OBSERVATIONS AT MOUNT WASHINGTON.

It has already been stated that the preceding series of computations were undertaken because they afforded a means of comparing the work of the new method with the work of other barometric methods as exhibited by their authors and advocates. The value of the result is somewhat impaired, however, by the fact that none of the groups of stations are strictly appropriate to the execution of such a test. Placerville and Hope Valley are 46 miles apart, Summit and Sacramento 77 miles, Geneva and St. Bernard 55 miles; and each of these distances introduces into the problem a large element of gradient, alike annual, perennial, and non-periodic. Neither the new method nor any of the three with which it has been compared undertakes to eliminate this gradient, and the presence in all the computations of a considerable error derived from this source cannot but have the effect of obscuring the actual accomplishment of each scheme of devices in the elimination of the errors to which it is theoretically adapted. Search was therefore made for a locality where the test might be repeated with base and new stations all comprised within a small radius, so that no considerable gradients, aside from those with a diurnal period, could enter; and Mount Washington was found to answer the purpose.

In the year 1873 the United States Signal Corps, under the direction

of the late General A. J. Myer, conducted a series of hourly observations extending through the month of June at four stations upon the summit and flank of Mount Washington. The vertical space between the highest and lowest stations was about 3,600 feet, and the horizontal distance 3 miles. The observations were published in full in the Annual Report of the Chief Signal Officer, and numerous accessory data pertinent to the purpose of the writer have been furnished him from the original manuscript records through the courtesy of the present chief, General W. B. Hazen.

The stations are indicated by numbers, Station 1 being upon the summit of the mountain, Station 4 at its base, and Stations 2 and 3 upon the intervening slope. The altitude of Station 1 above the ocean has been determined by spirit level to be 6,285.4 feet,* but the other stations have not been connected by leveling. By means of simultaneous barometric readings at Station 1, Station 4, and Portland, Maine, the altitude of Station 4 has been computed by the new method, and with Station 1 and Station 4 as bases the altitudes of the intervening stations have been similarly computed. The relations of the four stations appear by the following table†:

	Above 2.	Above 3.	Above 4.
Station 1	779	2,355	3,607
Station 2	....	1,576	2,828
Station 3	....	....	1,252

The month of June, 1873, witnessed no notable storm, but its variety of weather nevertheless left room for selection; and the meteorologic record was carefully examined for the purpose of choosing the portion of it most favorable for hypsometric determinations. A period of eight days, beginning with the 22d and closing with the 29th, was selected as one of exceptional quiet, involving less wind than any similar period in the month, and therefore offering a series of observations comparatively free from non-periodic gradients. The observations for these days were plotted upon section paper for convenience of scrutiny, and all which revealed themselves as anomalous were investigated for the detection of errors of observation or reduction. A number of errors

* This is the altitude reported in connection with the record of observations. Its accuracy has recently been brought in question by the Signal Office, and it is possible that a correction to it will be made.

† The determinations given in the table were made at the commencement of this investigation; and some of the observations on which they are based were afterward ascertained to be untrustworthy. They are therefore not the best which could be deduced. The work was not repeated, first, because a more accurate set of determinations could not modify the result of the comparative test, and second, because the uncertainty affecting the altitude of the summit station rendered a satisfactory set of determinations impracticable.

of both kinds were detected and corrected,* and the observations were then made the basis of a series of computations for the purpose of illustrating the relative precision of different hypsometric methods.

* To any person who in the future may have occasion to use the observations published on pages 687 to 757 of the Annual Report of the Chief Signal Officer for 1873, it will be advantageous to note the following *corrigenda*. They all apply to the numbers in the column headed "Corrected barometer."

Page 687, Station 2, 1 a. m., for "24.633" read 24.731.
Page 687, Station 2, 4 a. m., for "24.784" read 24.684.
Page 691, Station 2, 10 p. m., for "24.571" read 24.671.
Page 698, Station 1, 8 p. m., for "23.541" read 23.521.
Page 705, Station 2, 4.57 p. m., for "24.500" read 24.700.
Page 705, Station 1, 7 p. m., for "24.020" read 24.024.
Page 707, Station 1, 7 a. m., for "24.993" read 23.993.
Page 711, Station 3, 3 a. m., for "28.856" read 25.856.
Page 713, Station 2, 8 p. m., for "24.450" read 24.480
Page 713, Station 3, 4 a. m., for "26.999" read 25.999.
Page 713, Station 2, 6 a. m., for "24.442" read 24.542.
Page 714, Station 1, 1 p. m., for "23.890" read 23.878.
Page 719, Station 4, 12 m., for "27.240" read 27.249.
Page 719, Station 4, 4.57 p. m., for "27.081" read 27.181.
Page 734, Station 1, 12 p. m., for "23.469" read 23.489.
Page 735, Station 4, 4 a. m., for "23.496" read 23.498.
Page 739, Station 3, 1 a. m., for "26.111" read 26.121.
Page 739, Station 4, 4 a. m., for "27.367" read 27.387.
Page 742, Station 3, 5 a. m., for "26.183" read 26.173.
Page 742, Station 1, 7 a. m., for "23.942" read 24.042.
Page 743, Station 3, 4.57 p. m., for "26.154" read 26.194.
Page 743, Station 3, 6 p. m., for "26.100" read 26.200.
Page 746, Station 3, 5 a. m., for "26.489" read 26.389.
Page 748, Station 2, 2 a. m., for "24.781" read 24.739.
Page 749, Station 1, 11 a. m., for "24.985" read 23.985.
Page 749, Station 1, 12 m., for "24.965" read 23.965.
Page 749, Station 2, 1 p. m., for "24.733" read 24.633.
Page 751, Station 4, 2 a. m., for "27.112" read 27.012.
Page 752, Station 1, 1 p. m., for "27.742" read 23.742.

In all these cases the error of the printed numbers is demonstrated by comparing them with the published uncorrected barometer readings and the published readings of the attached thermometer. There are, however, a number of instances in which the published figures are manifestly erroneous, yet do not afford the data for their own correction. In every such case the recorded reading was rejected, and one more accordant with its companions in the series was substituted for use in the computations. These changes were made sparingly and cautiously, and it is believed that no aberration of natural origin has been referred to an error of observation,—but that, on the contrary, a large number of errors of observation were passed by. Only three of these arbitrary changes affect observations of the eight-day series described in the text in this place, but all of them affect the data of computations made for some portion of the present paper. In the following enumeration no attention is paid to the figures of the column headed "Barometer," although they need to be similarly modified. The quoted figures are from the column headed "Corrected barometer."

Page 688, Station 1, 11 a. m., for "23.827" substitute 23.877.
Page 689, Station 1, 8 p. m., for "23.746" substitute 23.846.

In the conduct of this inquiry two limits were recognized. In the first place, since the new method aspires to supersede antecedent methods only in the performance of such work as falls to the lot of surveys—work in which many new stations are to be determined in a restricted area—no methods were considered which appeared inapplicable to that object. The sole case considered was that in which a single observation at a new station is compared with a single observation at a base station, or at each of several base stations, with such aid as may be derived from the other observations of a continuous series at the base stations. Restricted as this problem appears to be, it is nevertheless the one which practically arises in nine-tenths of the hypsometric work performed with the barometer.

The second limit confined attention to methods known to be actually in use, for manifestly it would be a work of supererogation to undertake in this place to test the efficiency of those tentative methods which have not in practice won a place for themselves.

The methods in actual use which are adapted to the ordinary needs of geographic work fall readily into two classes, the first of which employs in the computations only the data afforded by the field notes, while the second adds to these data certain empiric corrections derived from long series of observations. Of the first group, the method of Williamson is a representative; and since, in the opinion of the writer, it has no superior in its class, it was selected as a typical example to be used in the comparison. The second class includes among others the systems of Plantamour and Whitney; and while its members differ somewhat in their manners of deducing and applying empiric corrections, they attain so nearly the same result that it matters little which one is selected as representative. The one already described as devised by Whitney was employed, the selection being determined chiefly by the fact that his method of procedure is so fully and clearly set forth that it can be repeated without danger of mistake.

Page 689, Station 4, 8 p. m., for "27.208" substitute 27.228.
Page 698, Station 1, 6 p. m., for "23.561" substitute 23.511.
Page 700, Station 2, 4.57 p. m., for "24.452" substitute 24.352.
Page 707, Station 1, 6 p. m., for "24.016" substitute 23.916.
Page 714. Station 1, 10 a. m., for "23.925" substitute 23.825.
Page 718, Station 1, 7 a. m., for "24.012" substitute 23.912.
Page 720, Station 1, 1 a. m., for "23.910" substitute 23.810.
Page 720, Station 1, 2 a. m., for "23.905" substitute 23.805.
Page 721, Station 2, 11 a. m., for "24.440" substitute 24.460
Page 722, Station 4, 9 p. m., for "27.072" substitute 27.052.
Page 732, Station 4, 1 a. m., for "26.909" substitute 26.809.
Page 733, Station 2, 6 p. m., for "24.219" substitute 24.241.
Page 734, Station 1, 10 p. m., for "23.491" substitute 23.541.
Page 735, Station 4, 6 a. m., for "26.961" substitute 27.011.
Page 735, Station 1, 7 a. m., for "23.646" substitute 23.546.
Page 739, Station 4, 3 a. m., for "27.342" substitute 27.372.
Page 745, Station 2, 12 m., for "24.906" substitute 24.945.
Page 747, Station 2, 3 p. m., for "24.926" substitute 24.860.

The restriction of the problem to the case in which only a single observation at the new station is employed made it impracticable to apply Williamson's method in its entirety, for he introduces a correction for the diurnal oscillation of the barometer at the new station, and that correction can be determined with accuracy only by the aid of a series of observations of some extent. He does not recommend the occupation of each individual station for the period necessary to determine its diurnal pressure cycle, but uses instead the known cycle of some other station conceived to be characterized by the same conditions; and there is a sort of uncertainty attaching to this practice which it was impracticable to represent in this series of computations. By omitting all correction for diurnal oscillation, an apparent injustice is done Williamson's method: but if the observations were corrected by means of diurnal curves derived from the *same* observations, an equally unfair advantage would be given, because no such facilities are afforded in practical hypsometry. The uncertainty attaching to the substitution of the diurnal pressure curve of one locality for that of another is so great that I am disposed to doubt the advantage of Williamson's "horary correction" in all cases where the new station affords but a single observation.

Failing thus to apply all of Williamson's rules in the computations, I have hesitated to connect his name with the results. Suffice it to say that while it is probable that they fairly represent the application of his system to the postulated case, it is nevertheless possible that in general practice his method would appear in a more favorable light.

In the application of Whitney's method there was no similar difficulty. The Californian tables were not employed, because their use is restricted by their author to the vicinity of the Sierra Nevada, but a special table was constructed for the time and place in a manner presently to be detailed.

The observations having been freed from error, so far as practicable, and the plan of comparison having been arranged, the computations were then performed in the following manner:

In the first place the altitude of Station 2 was computed by the new method, making use of Stations 1 and 4 as bases, and a separate determination was made for each hour of the day for the period of eight days, making 192 independent determinations. The same work was then repeated with Station 3, giving a total of 384 determinations by the new method.

Colonel Williamson's method was then applied to the determination of the heights of Stations 2 and 3, first with Station 1 as a reference station or base and then with Station 4. The total number of these determinations was 768, and each of them was comparable with one of the determinations by the new method. The method of computation was as follows: An approximate difference of altitude was first derived from the barometer readings by the aid of Williamson's Table D_1. To this a correction for temperature was then applied, the correction being fur-

nished by his Table D_{II}, and being determined by the mean temperature of the day instead of the temperature of the hour. That is to say, for each of the eight days computations were made of the mean temperatures at the base station and new station, and the half sum of these temperatures was taken to represent the mean temperature of the air column for *each* of the twenty-four hours of the day. The correction for moisture was determined from the means of the psychrometer readings for each day, and was found to be so nearly uniform that no distinction was necessary, and the same correction was therefore applied to all the determinations of each station. The corrections for gravity were regarded as constant at each station through the entire period.

In the application of Whitney's method the first process was the same as in the case of Williamson's, but in the determination of the correction for temperature, the thermometer readings at the two stations at the individual hours were employed instead of the daily means. No correction was applied for humidity, and the corrections for gravity were regarded, as before, as constant. Finally a special empiric correction was added, which had been derived from the observations for the entire month in the following manner: Monthly means were taken of observations of pressure and temperature made at Station 1 and Station 4, at the hours of 3, 6, 9, and 12 a. m. and 3, 6, 9, and 12 p. m., and from these means eight values of the difference of altitude were obtained, the method of computation being identical with that afterward employed for the individual observations. These values were compared with the assumed altitude (3,607 feet) and the differences were called corrections. By the aid of a plotted curve their irregularities were slightly diminished and values were interpolated for the remaining hours of the twenty-four. These corrections were applicable directly to computations of the difference in altitude of Stations 1 and 4, and in applying them to the smaller intervals involved in the determination of Stations 2 and 3 they were proportionately diminished.

It will be observed that the stations upon which the table of corrections was based are the same stations afterward used as bases or reference stations in the computations, and it is also true that the new stations lie in the direct line between them. The series of observations affording the table include the series of observations to which the corrections were applied. The table, therefore, was not merely adapted to the White Mountains and to the average month of June, but to the specific locality and to the individual June from which the illustrative computations were made. It cannot often occur in the use of a system involving empiric corrections that the conditions under which it is applied are so favorable.

In the comparison of the various results of these computations the lack of an independent and trustworthy standard had again to be regretted, and no better measure of precision was afforded than the internal harmony of the several series of determinations. The mean of each

series was calculated independently and was then subtracted from the several individual determinations. The series of differences thus obtained were then added so as to show the sum of each series independently of sign, and the several sums were divided by the number of terms. Each quotient gave the mean residual of a series of 192 determinations. The publication of the individual determinations of altitude is omitted by reason of their great number, and because the absence of a standard determined by leveling deprives them of any permanent value. The mean residuals are given in Table XXII. Each of the intermediate stations (2 and 3) was computed by the older methods by reference to Station 1 and Station 4 separately, while the new method used the two base stations conjointly. Each individual determination by the new method was therefore comparable with two distinct determinations by each of the others. In the table a single column only is given to the residuals by the new method, while each of the other methods is furnished with two columns for the corresponding residuals and a third to exhibit the mean of the preceding two.

TABLE XXII.

Comparison of Barometric Methods by means of Computations from Observations at Mount Washington, N. H., in June, 1873.

New Station.	Average Deviation from Mean of 192 Determinations.						
	By New Method, Station 1 and Station 4 as Bases.	By Method with One Base Station and No Empiric Correction. (Williamson.)			By Method with One Base Station and Local Empiric Correction. (Whitney.)		
		Referred to—		Mean of two series.	Referred to—		Mean of two series.
		Station 1.	Station 4.		Station 1.	Station 4.	
	Feet.	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*
Station 2	11.8	15.1	15.8	15.5	14.4	13.5	14.0
Station 3	8.9	21.8	7.9	14.9	18.1	9.9	14.0
General Mean	10.4	....	....	15.2	....	....	14.0

The general result, as indicated by the footings, is that the average residual afforded by the determinations when one base station is employed and no empiric correction is used is 50 per cent greater than the residual when two base stations are employed by the new method; and that when the method with a single base station is modified by the use of local empiric corrections, the average residual is 40 per cent greater than that obtained with two bases.

After Table XXII had been prepared and the preceding paragraph had been written, the discovery was made that the observations on Mount Washington were affected in a peculiar and systematic way by certain high winds, so that a considerable share of their error is of an

exceptional nature and so far avoidable that it may be considered not to affect the hypsometric problem strictly considered. A full account of this influence of the wind will be found in the fourth section of Chapter IV. In order to make sure that this special condition did not vitiate the conclusion reached above in regard to the comparative accuracy of hypsometric methods, the full series of 192 determinations was scrutinized with reference to the associated wind, and each determination made at a time when the wind at any one of the four stations exceeded ten miles per hour was rejected. The remaining determinations (which number 74 in each series) were then discussed by themselves in the same manner as the entire series had previously been. Their mean residuals are given in Table XXII *bis*.

TABLE XXII *bis*.

Comparison of Barometric Methods by means of Computations from a Selected Series of Observations at Mount Washington, N. H., in June, 1873.

New Station.	Average Deviation from Mean of 74 Determinations.						
	By New Method, Station 1 and Station 4 as Bases.	By Method with One Base Station and No Empiric Correction. (Williamson.)			By Method with One Base Station and Local Empiric Correction. (Whitney.)		
		Referred to—		Mean of two series.	Referred to—		Mean of two series.
		Station 1.	Station 4.		Station 1.	Station 4.	
	Feet.	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*
Station 2	7.7	8.7	·17.7	13.2	9.2	12.9	11.0
Station 3	6.2	17.6	7.8	12.7	9.2	9.9	9.6
General Mean	7.0	....	....	13.0	....	....	10.3

The result of the second comparison is even more favorable to the new method than that of the first. The mean residual of the determinations by Williamson's method is 85 per cent greater than that by the new, and the residual by Whitney's is nearly 50 per cent greater. The new method does not suffer in comparison when the observations are improved.

COMPARATIVE COMPUTATIONS FROM MONTHLY MEANS.

When single sets of observations, made at individual hours, are employed in the computations of heights, the results are subject to all sources of error, but if the observations are first grouped in certain ways, so as to obtain mean values, certain classes of errors are practically eliminated. When the means of all the observations on a single day are employed, the results are freed from errors having a diurnal period; when monthly means are employed, the errors arising from non-periodic

gradient are greatly diminished; and if annual means be employed, little remains but perennial gradient and constant errors dependent on temperature. When long series of monthly means are used, the fact is developed that there are inequalities dependent upon season which tend to repeat themselves from year to year. The ability of the new method to eliminate such inequalities has been tested in Table XII, where its results are compared with those given by Whitney's tables, but its performance in this regard has not yet been compared with that of the simpler hypsometric methods. Table XI indeed contrasts the results obtained by Williamson and by the new method for certain Californian stations in the months of June and January, but the result is unsatisfactory. In the first place there is no fixed standard of comparison, and in the second the number of terms in each series of determinations is too small to exclude the possibility of fortuitous accordance or discordance. The series of observations and computations published by Williamson afford no material adapted to a more extended comparison, and indeed there appear to be no published observations well suited to the purpose, but the need is partially met by the observations published by Whitney. Those observations cover a period of thirty-five months, and, as published, afford monthly means of barometric pressure and atmospheric temperature. They do not, however, contain the data necessary to the computation of the correction for humidity, and they therefore fail to accord to such a method as that of Williamson the means of producing its best results. When the observations at individual hours are considered it is probable that the harmony of results is enhanced by ignoring the psychrometric observations, but when monthly means furnish the data for computation there is an advantage in employing them. Despite this defect, the Californian observations are the best available, and a series of computations has accordingly been made from them.

For each of the thirty-five months a determination of the altitude of Colfax has been made by using Sacramento and Summit as bases, and the error of each determination has been ascertained by subtracting from it 2,399 feet—the difference in altitude established by leveling. The altitudes and errors are given in full in Table XXIII. The comparative computations were not made by the writer, because that work had already been performed by Professor Whitney. His results, with their corresponding errors, were transferred from pages 75–79 of his treatise, and incorporated in the same table (XXIII). They form two series: the first gives the determinations of Colfax when Sacramento was used as a base station; the second when Summit was thus used.

In the computations by Professor Whitney the tables of Williamson were employed for all elements except the temperature and humidity, and Guyot's formula was applied for the derivation of the temperature corrections.

TABLE XXIII.

Comparative Determinations of the Altitude of Colfax above Sacramento, Cal., from Monthly Means of Thrice-daily Observations.

Date.	By New Method, from Sacramento and Summit.		By Old Method, the Base Station being— Sacramento.		By Old Method, the Base Station being— Summit.	
	Altitude.	Error.	Altitude.	Error.	Altitude.	Error.
1870.	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*
October	2391.0	− 8.0	2393.4	− 5.6	2454.3	+ 55.3
November	2386.5	− 12.5	2386.5	− 12.5	2462.1	+ 63.1
December	2391.7	− 7.3	2389.5	− 9.5	2479.6	+ 80.6
1871.						
January	2398.1	− 0.9	2380.2	− 18.8	2454.9	+ 55.9
February	2394.9	− 4.1	2402.8	+ 3.8	2424.7	+ 25.7
March	2391.3	− 7.7	2412.9	+ 13.9	2410.9	+ 11.9
April	2386.3	− 12.7	2410.6	+ 11.6	2389.2	− 9.8
May	2409.5	+ 10.5	2435.6	+ 36.6	2380.7	− 18.3
June	2410.3	+ 11.3	2430.3	+ 31.3	2362.3	− 36.7
July	2420.2	+ 21.2	2435.5	+ 36.5	2376.7	− 22.3
August	2415.0	+ 16.0	2424.9	+ 25.9	2390.6	− 8.4
September	2411.6	+ 12.6	2409.6	+ 10.6	2407.9	+ 8.9
October	2412.1	+ 13.1	2398.9	− 0.1	2432.7	+ 33.7
November	2389.9	− 9.1	2389.9	− 9.1	2413.8	+ 14.8
December	2398.8	− 0.2	2400.9	+ 1.9	2404.1	+ 5.1
1872.						
January	2400.7	+ 1.7	2395.4	− 3.6	2433.0	+ 34.0
February	2375.9	− 23.1	2397.5	− 1.5	2372.3	− 26.7
March	2390.1	− 8.9	2412.4	+ 13.4	2392.9	− 6.1
April	2391.1	− 7.9	2429.2	+ 30.2	2391.0	− 8.0
May	2400.3	+ 1.3	2431.1	+ 32.1	2391.1	− 7.9
June	2396.3	− 2.7	2416.5	+ 17.5	2371.3	− 27.7
July	2416.7	+ 17.7	2440.6	+ 41.6	2375.6	− 23.4
August	2387.5	− 11.5	2415.1	+ 16.1	2382.4	− 16.6
September	2385.4	− 13.6	2389.3	− 9.7	2389.2	− 9.8
October	2381.7	− 17.3	2372.9	− 26.1	2391.4	− 7.6
November	2407.0	+ 8.0	2392.1	− 6.9	2435.5	+ 36.5
December	2400.3	+ 1.3	2381.2	− 17.8	2449.5	+ 50.5
1873.						
January	2371.6	− 27.4	2393.3	− 5.7	2419.1	+ 20.1
February	2357.3	− 41.7	2402.8	+ 3.8	2375.5	− 23.5
March	2378.0	− 21.0	2417.3	+ 18.3	2407.3	+ 8.3
April	2402.0	+ 3.0	2472.8	+ 73.8	2390.9	− 8.1
May	2387.0	− 12.0	2454.4	+ 55.4	2369.4	− 29.6
June	2407.1	+ 8.1	2474.7	+ 75.7	2370.7	− 28.3
July	2402.0	+ 3.0	2451.2	+ 52.2	2370.8	− 28.2
August	2400.4	+ 1.4	2469.5	+ 70.5	2321.3	− 77.7
Mean	....	10.8	....	22.8	....	26.5

The footings of the several columns of errors indicate that the new method is greatly superior to the old in its ability to produce uniform results at different seasons of the year. The old method gives a better series of determinations with Sacramento as a base station than with

Summit, but even in that case its average error is more than twice as great as that by the new method. The disparity is so great as to render it improbable that the comparison would be materially affected by the introduction of the humidity correction.

SUMMARY.

By the preceding series of tests the new hypsometric method has been compared with the two general methods already in use. It will be convenient to designate these older methods by the words *ordinary* and *empiric;* indicating by the title *ordinary* the general method which employs a single base station only, and applies the formula of Laplace or that of Bessel with no special corrections not readily derivable from a short series of observations at the base station; and indicating by the title *empiric* the general method which introduces into the computation an empiric correction derived from a long series of observations made at two stations in the vicinity of the point to be measured.

The special procedure which has been used as an example of the ordinary method is that of Williamson, and its chief individual peculiarities consist in the rejection of the thermometric and psychrometric observations at the moment of barometric measurement and the substitution therefor of diurnal means of thermometric readings and weekly or monthly means of psychrometric readings. A point in California was found which had already been subjected to a series of determinations by Williamson, and which was at the same time well conditioned for the application of the new method. Ninety corresponding determinations by the new method afforded a mean error 53 per cent less than the mean given by the ordinary. A series of 384 computations from observations on the slopes of Mount Washington gave a mean error 32 per cent less than by the ordinary; and a series of 148 computations, selected from the last by reason of specially favorable conditions of observation, gave a mean error 46 per cent less than by the ordinary. In the case of the Californian work, the stations involved were at such distance that the observations and results were presumably largely influenced by cyclonic gradients, while at Mount Washington they were not. The tests at the second locality are therefore more valuable as indicative of the ability of the two methods to eliminate those errors to which alone they are applicable. Doubtless, if the computations were repeated from observations in other localities, or from observations in the same locality at another season of the year, notably different results might be obtained; but, in the absence of the necessary observations, we cannot do better than accept the Mount Washington results, and say that under conditions favorable to the application of both methods the substitution of the new for the ordinary reduces the error nearly one-half.

In comparing the new method with the empiric, illustrations were derived from Whitney's work in California and from Plantamour's in the Alps, and a computation after the manner of Whitney was applied to the Mount Washington observations. Eighty-six comparative determinations of Colfax, Cal., indicated a reduction of error by the new method of 35 per cent; 106 determinations of stations in various parts of California indicated a reduction of 10 per cent; 82 determinations of stations in the Alps, a reduction of 39 per cent; 384 determinations at Mount Washington, a reduction of 26 per cent; and 148 determinations at Mount Washington, from observations not affected by wind, a reduction of 32 per cent.

Here again all the determinations, except those at Mount Washington, were exposed to the influence of cyclonic gradients, but in such way that it is impossible to say whether one method was favored more than the other. The weighted mean of all the indicated reductions is 27 per cent, and from the data at hand we cannot do better than adopt that as the measure of the gain when the new method is substituted for the empiric.

All the computations referred to in the preceding paragraphs were based upon individual observations, and, with the exception of those for the determination of Colfax, were checked by no standards more authoritative than their own mean results.

The period of observation for each of these series is so short that it cannot be considered to include those variations dependent upon season of year; but the comparison has been extended so as to develop the ability of the several methods to cope with them. From Table XI and Table XXIII it appears that the new method reduces, by about one-half, the error incurred by the application of the ordinary method to monthly means; and Table XII shows that it equals the performance of the empiric method under conditions especially favorable to the latter. The error related to the season is not so great as the error related to the day and hour, but it is still not unimportant, and the superior ability of the new method to cope with this gives it an added advantage over the ordinary. Expunging, as compared with the ordinary, nearly one-half of the error related to the hour, and fully one-half of the error related to the season, it may with propriety be credited with a diminution of the total error of a single computation by about one-half. Equaling the empiric method in its ability to obviate seasonal irregularities, its relative power to cope with the total error of an individual computation is approximately measured by its relative power to cope with that element of error which pertains to the hour—a power indicated, as we have seen, by an improvement of 27 per cent.

If it be granted that the new method effects a reduction of one-fourth the error of the empiric and of one-half the error of the ordinary, it must of necessity be admitted that it is the more exact hypsometric method; but it does not necessarily follow that it will, or should, supplant them, for

other conditions need to be satisfied. Of these we shall speak more fully in another chapter, here mentioning only the single consideration of cost. In the application of the ordinary method to the work of a survey, a barometer, or a number of barometers, are carried during the season of field operations from one new station to another and are read at each; during the same period a single base station is maintained continuously; and these are the only items of expense, unless it is also necessary to determine in some independent way the altitude of the base station. A similar application of the new method involves all these expenses, and, in addition, the cost of maintaining a second base station throughout the same period and of measuring with the level the difference in altitude of the two bases. For the similar application of the empiric method the outlay of the ordinary method is required during the season of field work, and it is additionally demanded that two stations in the vicinity shall have been antecedently maintained for a term of years. In every case, therefore, the empiric and new methods are more expensive than the ordinary, and in most cases the empiric is more expensive than the new. It may sometimes occur, as, for example, in the Alps, that the preliminary labors necessary for the application of the empiric method have already been performed for other purposes, and in such case that method can be as economically applied as the ordinary. It may also occur that the continuance of geographic work in the same district for a series of years will enable the empiric method to use for its base stations the identical observatories and observations employed for the deduction of its tables of corrections, and in such cases its expense is practically identical with that of the new method.

In the more frequent cases the empiric method is more expensive than the new, and there can be no reason for employing it. When circumstances place them on a parity in the matter of expense, the preference should go to the new method on the score of precision. But when the new method is compared with a less expensive application of the empiric, or with the comparatively inexpensive ordinary method, we may conceive that there will always be a weighing of utility *versus* cost, and various extraneous circumstances may determine the use of the one or the other.

The rarity of the circumstances which should lead to the preference of the empiric method may be supposed to narrow the choice in most cases to the ordinary on the one hand and the new on the other. As will be shown in the sequel, there is a considerable range of special cases in which the ordinary method can never be superseded by the new.

CHAPTER IV.

POSSIBLE IMPROVEMENTS.

In the preceding chapters an attempt has been made to give the new method a rationale and a *raison d'être*,—to show first that it is theoretically plausible, and second that it is practically successful. It has been pointed out that while the hypsometric methods now in use strive to ascertain the momentary density coefficient of an air column in an indirect way, by untrustworthy measurements of temperature and moisture, the new method undertakes to determine it by means of a direct measurement of the simultaneous density coefficient of a partially coincident air column. It has been shown that the only arbitrary assumption involved in the new departure—the assumption of a simple law for the vertical variation of the density coefficient—is so far unavoidable that it has been embodied in all the older practice. And it has been shown by an extended series of comparative computations that the application of the new formula actually accomplishes a diminution of hypsometric error. In the present chapter it will be assumed that the new method is destined to find a place in the hypsometric work of the future, and consideration will be given to the possibility of further developing it so as to increase its usefulness. Its merits having been sufficiently dwelt upon to establish its claim to recognition, its shortcomings will now be discussed with a view to their amelioration.

1. REDETERMINATION OF THE CONSTANT.

In the thermic term of the formula, $\frac{A(B-A)}{D}$, the quantity D is a constant, but it is not one which admits of determination from *a priori* considerations. Its value can be learned only by applying the formula to the computation of known heights, from means of long series of observations. To accomplish this in a satisfactory manner it is necessary to use a group of three stations whose differences in altitude are both great and known, and whose horizontal distances are small. There is no published long series of observations at stations fulfilling these conditions, and the value assigned to D, 490,000 feet, is merely provisional. It was derived, as has already been explained, from a two years' series of observations made in California at a group of stations of which the extreme members are 77 miles apart, and its accuracy is impugned by many considerations. In the first place, the values afforded by the two

years, considered separately, are not closely accordant, while those afforded by the four half years into which the same series of observations may be divided are highly discordant. In the second place, the highest and lowest stations of the group are not merely widely separated, but one of them is in close proximity to the ocean, so that the observations are subject to the unfavorable influence, not only of non-periodic gradients, but of the annual and perennial gradients of a coast district, which theoretically are exceptionally great. In the third place, the leveling by which the altitudes of the stations were determined was not performed with special reference to this or any other scientific object, but merely for the less exacting needs of a railroad, and its guaranty of precision is insufficient. In the fourth place, a portion of the observations are of poor quality. The observers were chiefly occupied with other duties, and at two stations they were frequently changed. Their records are not perfectly continuous and are not free from patent errors. And, finally, the observations were restricted to the hours of 7 in the morning and 2 and 9 in the afternoon, and no other data exist for ascertaining the daily means. In observations of atmospheric temperature, it has been found that readings at these three hours enable the daily mean to be computed with a high degree of precision, and this at all seasons of the year; but the same rule does not apply to observations of atmospheric pressure. The daily cycle of pressure has it maximum at different hours in different seasons and at different stations, and the mean of the readings at the hours of 7, 2, and 9 frequently differs from the mean for the day by amounts which affect hypsometric results to the extent of several feet.

In comparing computations by the new method with corresponding computations by Professor Whitney for the determination of altitudes at various points in California, there was found to be a difference of a constant nature which would be explained if it should be discovered that the middle station of the Californian group had been assigned by leveling too low an altitude. The effect of such an error upon the estimate of D would be to make it too great. In the comparison, too, of Alpine altitudes computed by the new method, with corresponding altitudes computed by Professor Plantamour, there was found a discrepancy of a constant nature which would be explained if the assumed value of the constant D were ascertained to be too large. There is therefore a presumption that its real value will eventually be found to be somewhat smaller than the one provisionally assigned it.

The desiderata for the final and satisfactory computation of the constant are a series of barometric observations, made at every hour for a period of not less than two years, at three stations whose vertical relations are definitely known, the highest being separated from the lowest by a vertical space of several thousand feet and by a small horizontal space, and the intermediate station being approximately medial. An inland locality is preferable.

The table appended to this paper as an aid to the computer in the use of the formula, is based upon the provisional value of the constant, and will need to be changed when a more satisfactory value is obtained. Its reconstruction will not be a matter of difficulty, since it will merely be necessary to multiply each of its corrections by a constant factor.

2. PROVISION FOR DIURNAL PERIODICITY.

The factor of atmospheric density which finds expression in the thermic term of the formula is an inequality incited by the sun's heat. It would not be strange therefore if it should be affected by a periodicity dependent upon the periodicity of the reception of solar heat; and if it is, there would necessarily be a corresponding systematic inequality in the results given by the formula. Should such an inequality be discovered, it would be possible to make a counteractive modification of the formula and thereby increase its efficiency. The two principal thermic periods due to solar heat are the day and the year; and we will inquire, first, whether the altitudes computed by the formula exhibit any constant inequalities having a daily cycle.

To test the existence of a diurnal period we compute the same altitude by the aid of the same base stations at different hours of the day, and repeat the experiment for as many days and as many localities as practicable. If a diurnal change occurs it is easy to understand that it may vary in character or amount from place to place and from season to season.

The computations made for the purpose of comparing the efficiency of different hypsometric methods, and described in the last chapter, afford a considerable body of material pertinent to this inquiry, and their results have been rearranged with reference to it.

The observations at Placerville, Strawberry Valley, and Hope Valley, which form the basis of the results contained in Table III, were more extended than that table indicates. Colonel Williamson employed in his test computations only the readings made for ten days, at 7 in the morning and 2 and 9 in the afternoon, and the comparative computations by the new method were given the same limit. The observations were made, however, at every hour from 7 in the morning until 9 at night, and through the courtesy of Colonel Williamson, who kindly furnished me a copy of the record, I have been enabled to compute the altitude of Strawberry Valley, with Placerville and Hope Valley as bases, for each of the daylight-hours of ten days in August, 1860. On two of the ten days local thunder storms occurred, rendering the results inapplicable to the present purpose and reducing the length of the series to eight days. The results are exhibited in Table XXIV, and graphically by Figure 1

in Plate LVI, and plainly show a systematic change. The determinations of altitude from 7 in the morning until 3 in the afternoon are all lower than the mean, while from 4 to 9 p. m. they are higher; and the amplitude of their curve, after making allowance for abnormal irregularities, is fully 20 feet. Determinations made in the early evening ascribe to Strawberry Valley a height greater by 20 feet than do determinations made in the middle of the day. The curve in Plate LVI was constructed from the mean of the eight-day series. Similar curves were drawn for each of the individual days, and were found to exhibit in each case, although less perfectly, the same diurnal cycle, thus demonstrating its recurrent character.

TABLE XXIV.

Variations of Altitude Determinations from Hourly Means of Eight-day Series of Barometric Observations. August.

Hour.	New station, Strawberry Valley. Base Stations, Hope Valley and Placerville. Height of New Line, 1,865 feet. Height of Base Line, 5,107 feet.	New and Base Stations on the Miesing. Height of New Line, 1,772 feet. Height of Base Line, 3,504 feet.
	Feet.	*Feet.*
7 a. m	− 2	....
8 a. m	− 6	+ 6
9 a. m	− 3	+ 5
10 a. m	− 8	− 4
11 a. m	− 9	+ 1
12 m	− 9	− 3
1 p. m	− 8	− 5
2 p. m	− 10	− 6
3 p. m	− 3	− 3
4 p. m	+ 4	− 1
5 p. m	+ 8	+ 4
6 p. m	+ 13	+ 5
7 p. m	+ 10	....
8 p. m	+ 12	....
9 p. m	+ 9	....

The observations made by Bauernfeind on the Miesing, to which reference was made in the discussion of the thermic constant (see Table II), have been utilized for the present purpose also. Like the last, they consist of an eight-day series in August and are limited to the daylight hours, the series beginning at 8 a. m. and ending at 6 p. m. The results of the computations, translated into English feet, appear in Table XXIV and in Figure 2 of Plate LVI. In this case no separate computation was made for the individual days, the available record of the observations containing only the means of the series; but the smoothness of the curve, which is interrupted by only a single aberrant term, vouches for the actuality of a diurnal period.

The Californian observations, to which our general investigation is

so greatly indebted, make a valuable contribution in this place also. In Table XII of the preceding chapter the right-hand pair of columns contain the errors of altitude determinations for Colfax by the new method for each month of the year and for each of the three hours of observation. In Table XXV the same results are given, with a different arrangement and combination, for the purpose of expressing more definitely the relations of the errors to hours of the day. In the reconstruction, the results for the two years were first combined so as to obtain means, and then the figures for each month were increased or diminished by the quantity necessary to eliminate the variation peculiar to the month as a whole. The footings of the columns in Table XXV and Figure 4 of Plate LVI give the general result of the comparison and show that the new method of computation when applied to the determination of Colfax from Sacramento and Summit as bases gives a result at 7 in the morning 11 feet greater than its result at 2 in the afternoon and 15 feet greater than its result at 9 in the evening.

TABLE XXV.

Showing the Relation of Variations in the Computation of Colfax from Sacramento and Summit to Hours of the Day, the Computations being from Monthly Means of Observations.

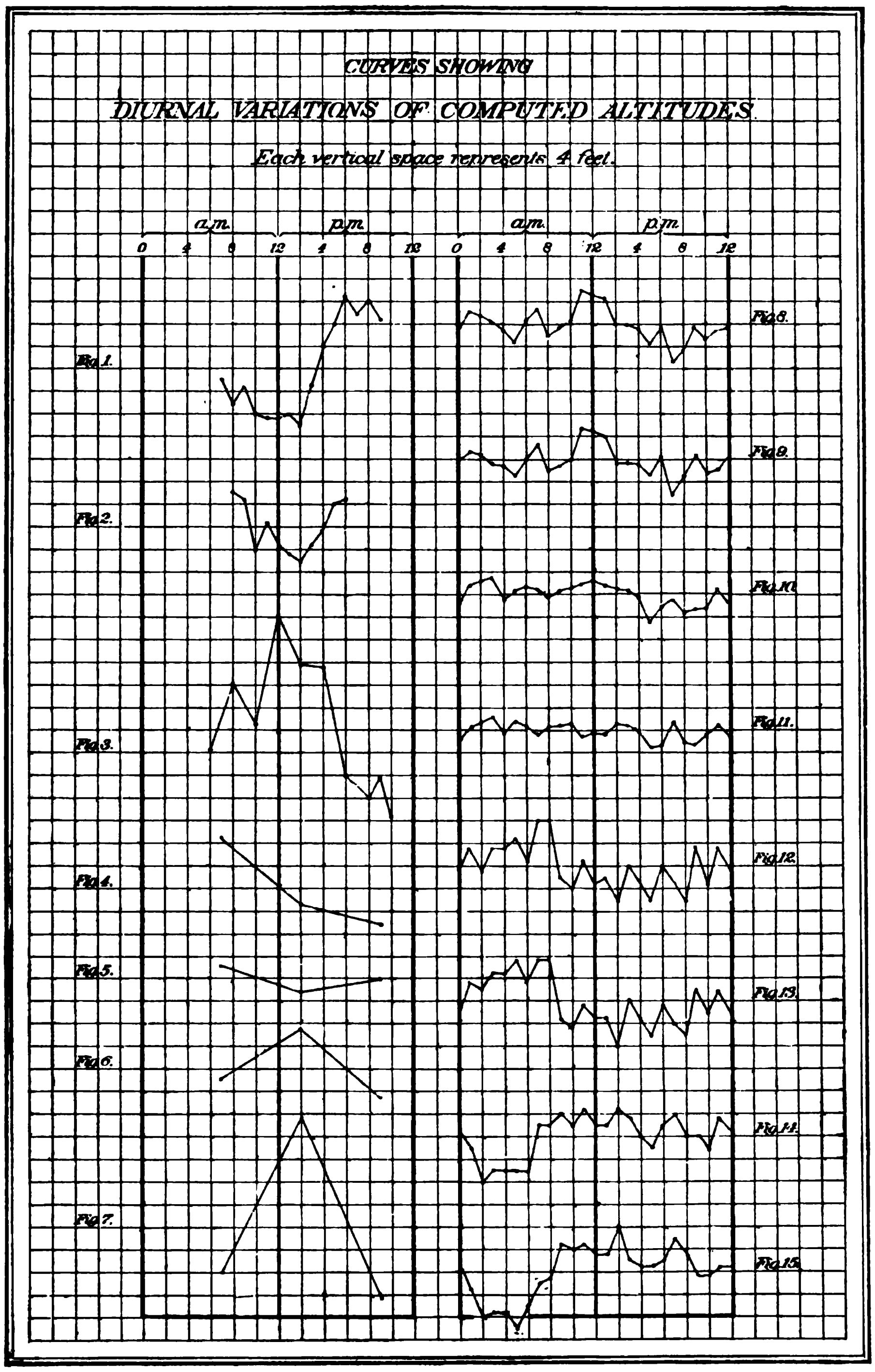
Month.	Variation from Monthly Mean, in feet.		
	7 a. m.	2 p. m.	9 p. m.
January	+ 2.5	+ 0.1	− 2.6
February	+ 1.0	− 2.4	+ 1.4
March	+ 8.0	+ 0.3	− 8.3
April	+ 7.9	− 2.9	− 5.0
May	+ 10.6	− 5.3	− 5.3
June	+ 14.3	− 4.8	− 9.5
July	+ 20.5	− 10.9	− 9.6
August	+ 9.6	− 0.7	− 8.9
September	+ 10.2	− 2.5	− 7.7
October	+ 10.9	+ 1.2	− 12.1
November	+ 12.3	− 3.4	− 8.9
December	− 0.9	− 1.2	+ 2.1
Mean	+ 8.9	− 2.7	− 6.2

NOTE.—The altitude of Colfax above Sacramento is 2,399 feet; of Summit above Sacramento, 6,989 feet.

The results for the individual months do not accord perfectly with those for the entire year, but they have sufficient harmony to guarantee that the general result is not due to accident but to an actual, systematic, periodic variation in some condition affecting the measurements. They show, moreover, that the diurnal cycle is itself subject to variations dependent upon season. Its amplitude is less in the three winter months than in the remainder of the year, and is greatest of all in the hottest month.

EXPLANATION OF PLATE LVI.

No. of Figure.	New Station.	Base Stations.	Period of Observation.	A= Height of New Station above Lower Base.	B= Height of Upper Base Station above Lower.	$\frac{A}{B}$
				Feet.	*Feet.*	
1	Strawberry Valley, Cal.	Hope Valley and Placerville.	8 days in August	3,742	5,107	.73
2	Station 3 on the Missing.	Station 5 and Station 1.	8 days in August	1,772	3,504	.51
3	6 points in the Alps.	St. Bernard and Geneva.	18 days in July, August, and September.	1,410 to 4,820	6,792	.21 to .71
4	Colfax, Cal	Summit and Sacramento.	2 years	2,399	6,989	.34
5	You Bet, Cal	Summit and Colfax	8 days in November and December.	550	4,590	.12
6	Gold Run, Cal.	Summit and Colfax	6 days in October	780	4,590	.17
7	Lakeport, Cal	Colfax and Sacramento.	9 days in October	1,320	2,399	.55
8	Station 2, Mount Washington.	Stations 1 and 4	Month of June	2,828	3,607	.78
9	Station 2, Mount Washington.	Stations 1 and 3	do	1,572	2,355	.67
10	Station 3, Mount Washington.	Stations 1 and 4	do	1,252	3,607	.28
11	Station 3, Mount Washington.	Stations 2 and 4	do	1,252	2,828	.44
12	Station 2, Mount Washington.	Stations 1 and 4	8 days in June	2,828	3,607	.78
13	Station 2, Mount Washington.	Stations 1 and 3	do	1,572	2,355	.67
14	Station 3, Mount Washington.	Stations 1 and 4	do	1,252	3,607	.28
15	Station 3, Mount Washington.	Stations 2 and 4	do	1,252	2,828	.44


CURVES SHOWING
DIURNAL VARIATIONS OF COMPUTED ALTITUDES.
Each vertical space represents 4 feet.
a.m.
p.m.
0
4
8
12
4
8
12
a.m.
p.m.
0
4
8
12
4
8
12
Fig. 1.
Fig. 2.
Fig. 3.
Fig. 4.
Fig. 5.
Fig. 6.
Fig. 7.
Fig. 8.
Fig. 9.
Fig. 10.
Fig. 11.
Fig. 12.
Fig. 13.
Fig. 14.
Fig. 15.

These monthly inequalities serve to warn us that a diurnal correction derived from observations at one season of the year cannot be applied in computations from observations made at another season.

TABLE XXVI.

Variations of Determinations in California, classified by Hours.

Station.	Altitude.	Height of Base Line.	Errors.		
			7 a. m.	2 p. m.	9 p. m.
			Feet.	*Feet.*	*Feet.*
Gold Run.	780 feet above Colfax.	4,590 feet.	−14.0	+ 7.2	− 1.2
			+ 3.0	+18.6	− 9.5
			− 6.9	− 1.7	....
			− 2.6	+ 9.5	−14.7
			+ 3.6	+ 7.7	− 1.6
			+ 5.0	+ 0.4	− 3.4
	Mean		− 2.1	+ 6.9	− 6.1
You Bet.	550 feet above Colfax.	4,590 feet.	....	....	+12.2
			+ 4.2	+ 4.8	+ 7.0
			+31.1	− 2.7	−16.3
			....	− 7.3	....
			....	− 3.3	....
			+ 3.0	−10.5	− 9.1
			− 4.7	+ 2.7	− 5.7
			− 8.1	....	....
			− 7.8	− 2.7	− 0.7
			+ 0.4	....	....
			+ 2.9	....	+10.5
	Mean		+ 2.6	− 2.7	− 0.3
Lakeport.	1,320 feet above Sacramento.	2,899 feet.	− 7	−12	−35
			−24	+21	−15
			....	+27	+ 8
			− 4	+39	....
			+32	−15	−39
			−45	+25	−20
			+17	+49	+ 4
			+ 5	+ 9	+19
			−37	+32	−26
	Mean		− 8	+19	−13

An inspection of the results embodied in Table XV shows that some of the variations in the heights computed by the new method exhibit periodicity. The series at Camp 9, Geyser Springs, and Long Valley are too short to afford trustworthy indications, but the remaining three not merely exhibit changes in the altitude determinations from one hour of observation to another but show a recurrence of these changes from day to day. In Table XXVI the variations of the determinations of altitude by the new method for the remaining three stations are arranged

according to hours of the day, and the means for each station are exhibited separately. The means are also plotted in Figures 5, 6, and 7, of Plate LVI. The diurnal variations in the determination of You Bet are somewhat similar to those in the determination of Colfax, but the variations at Gold Run and Lakeport are conspicuously different, the afternoon observations instead of the morning giving the maximum result.

A similar treatment was given to the variations shown by the determinations of altitudes in the Alps and embodied in Table XVIII, and the rearranged residuals will be found in Table XXVII. In this case the character of diurnal oscillation indicated by each of the stations is approximately the same, so that it seems preferable to take the means of the whole instead of individual means for the several stations. The hours of observation here include all those with even number from 6 in the morning until 10 in the evening, and the curve of variation (Figure 3, Plate LVI) is determined at so many points as to give it a definite character. Its maximum is in the middle of the day, its minimum occurs during the night, and its amplitude is in the neighborhood of twenty-five feet. Here again the recurrence of the diurnal change upon different days and at different stations testifies to its systematic nature.

TABLE XXVII.

Variations of Determinations in the Alps, classified by Hours.

New Station.	Altitude above Geneva.*	A. M.				P. M.					
		6	8	10	12	2	4	6	8	9	10
	Meters.	*m.*	*m.*	*m.*	*m.*	*m.*	*m.*	*m.*	*m.*	*m.*	*m.*
Grimsel	1,470	+ 1.2						− 2.8	−13.6		− 9.1
								0.0	+ 2.7	+4.4	
									+ 1.8		
Proz	1,400	+ 0.2		+1.9	+ 5.5	+ 2.8	+ 0.7	− 0.5	− 2.7		
		− 0.8						+ 1.5	− 6.8		
									− 1.2		
St. Pierre	1,230							− 2.6	− 8.6		
		− 8.0	+ 0.8	−1.6	+ 4.5	+ 6.1					− 6.8
		− 2.9	+ 3.6	+1.6		+ 2.8		− 2.0	− 0.6		
		+ 1.6	− 0.5					− 5.1	− 2.8		
			+ 4.7					+ 0.5	− 8.9		
									+ 3.1		
Evoléna	970	− 6.4				+ 6.8	+11.2	+ 1.0	− 7.7		
		− 1.4							− 2.7		
Chamounix	630	− 1.8	− 0.5	+2.4	+ 3.9	+ 0.3	− 2.1			−3.6	− 0.9
		+ 2.4					+ 3.8			−3.6	
Serraval	430	− 2.9	+ 5.0	−0.6	− 0.5	− 0.3		−11.7	− 9.8	−3.6	− 1.6
			− 0.9		+13.4	+ 7.1			− 4.4	−6.7	− 5.0
			+ 8.2		+10.9				− 1.8		− 4.1
Mean, in meters.		− 1.3	+ 2.5	+0.7	+ 6.3	+ 3.5	+ 3.4	− 2.2	− 3.6	−2.6	− 4.6
Mean, in feet.		− 3.6	+ 8.2	+2.3	+20.1	+11.5	+11.2	− 7.2	−11.8	−8.5	−15.1

*The height of the upper base station, St. Bernard, above Geneva is 2,070.3 meters.

The observations at Mount Washington have been made to afford eight independent curves of a similar nature. This variety of result has been obtained, first, by giving separate consideration to the entire month of June and to the eight June days selected for the comparative computations described in the last chapter, and, second, by combining the different stations in various ways as base and new. It will be remembered that the stations of observation were numbered, from highest to lowest, 1, 2, 3, and 4. In each computation of altitude by the new method three stations are used. There are therefore four different ways in which the stations may be grouped in the computations, each of the four stations being in turn omitted.

TABLE XXVIII.

Showing the Relation of Variations in the Computations of Altitudes on Mount Washington, N. H., to the Hours of the Day.

Hour.	Mean of Barometric Readings on Mount Washington for the Month of June, 1878.				Variation of Computed Altitude from its Mean Value.			
	Station 1.	Station 2.	Station 3.	Station 4.	Station 2, from Station 1 and Station 4.	Station 2, from Station 1 and Station 3.	Station 3, from Station 1 and Station 4.	Station 3, from Station 2 and Station 4.
	Inches.	*Inches.*	*Inches.*	*Inches.*	*Feet.*	*Feet.*	*Feet.*	*Feet.*
1 a. m.	23.8130	24.5119	25.9753	27.1711	+ 2.4	+ 1.8	+ 1.6	+ 0.5
2 a. m.	.8088	.5087	.9718	.1692	+ 1.8	+ 0.9	+ 2.4	+ 1.6
3 a. m.	.8042	.5057	.9679	.1669	+ 0.5	− 0.6	+ 3.2	+ 2.9
4 a. m.	.8008	.5054	.9736	.1719	− 1.1	− 0.9	− 0.8	− 0.4
5 a. m.	.8035	.5111	.9798	.1821	− 2.8	− 3.0	+ 0.5	+ 1.9
6 a. m.	.8094	.5141	.9853	.1887	+ 0.6	+ 0.1	+ 1.4	+ 1.0
7 a. m.	.8162	.5183	.9917	.1943	+ 3.2	+ 2.9	+ 1.0	− 0.5
7. 57 a. m.	.8199	.5259	.9948	.1951	− 1.7	− 1.7	− 0.2	+ 0.5
9 a. m.	.8277	.5311	.9970	.1951	− 0.5	− 0.7	+ 0.6	+ 0.7
10 a. m.	.8347	.5356	.9986	.1948	+ 0.6	+ 0.1	+ 1.4	+ 1.0
11 a. m.	.8397	.5335	.9967	.1896	+ 6.4	+ 5.7	+ 1.9	− 1.0
12 m.	.8407	.5335	.9921	.1824	+ 5.7	+ 4.8	+ 2.4	− 0.2
1 p. m.	.8389	.5319	.9886	.1772	+ 4.7	+ 4.0	+ 1.9	− 0.3
2 p. m.	.8343	.5306	.9823	.1686	0.0	− 0.3	+ 0.9	+ 0.8
3 p. m.	.8304	.5269	.9791	.1654	− 0.1	− 0.3	+ 0.7	+ 0.6
4 p. m.	.8257	.5225	.9744	.1592	− 0.7	− 0.6	− 0.3	− 0.1
4. 57 p. m.	.8183	.5183	.9725	.1541	− 3.8	− 2.2	− 4.6	− 3.1
6 p. m.	.8219	.5192	.9756	.1599	− 0.3	+ 0.6	− 2.7	− 2.6
7 p. m.	.8189	.5239	.9783	.1679	− 6.4	− 6.0	− 1.8	+ 1.4
8 p. m.	.8226	.5253	.9833	.1702	− 4.2	− 3.0	− 3.6	− 1.9
9 p. m.	.8278	.5272	.9877	.1763	− 0.3	+ 0.4	− 2.2	− 2.1
10 p. m.	.8266	.5282	.9809	.1762	− 2.5	− 1.9	− 1.8	− 0.8
11. 22 p. m.	.8231	.5247	.9848	.1781	− 1.3	− 1.4	+ 0.8	+ 0.8
12 midnight	.8184	.5192	.9820	.1738	− 0.3	+ 0.2	− 1.5	− 1.5
Mean	23.8219	24.5222	25.9833	27.1762	....	....	....	....

In each of the groups the highest and lowest stations were regarded as bases and the intermediate as new station. In each of the eight

cases the observations were arranged by hours, and means were taken, and from these means a separate determination of altitude was made for each hour of the twenty-four. Each determination was then compared with the mean of its own series and a set of residuals or variations derived. Table XXVIII gives the hourly barometric means for the month of June for each of the four stations, and gives also the variations from their several means of the corresponding determinations of altitude.

The same variations are plotted in Plate LVI, where they constitute Figures 8, 9, 10, and 11. The corresponding curves derived from the eight-day series of observations appear in Figures 12, 13, 14, and 15.

An inspection of the Mount Washington curves reveals some partial similarities, but none of a general nature. Curves 8 and 9 are closely alike, and so are curves 12 and 13, but the two pairs do not resemble each other. In all four the new station is the same, being Station 2. In curves 8 and 12 the base stations are Stations 1 and 4; in curves 9 and 13, they are Stations 1 and 3. The upper pair were derived from observations for the entire month; the lower pair from the eight-day series. The similarity of the members of each pair is due to the fact that the observations at the new station, which have a greater influence upon the result than the observations at either base station, are identical. The dissimilarity between the pairs arises from the fact that the series of observations from which they are derived, although the longer includes the shorter, are nevertheless inharmonious. The same remarks apply to the remaining curves. Figures 10 and 11 constitute a pair derived from monthly means with Station 3 as the new point; Figures 14 and 15, a pair derived from the eight-day means with Station 3 as new point.

The same disparity which exists between the curves for the entire month and the curves for the eight days is found when we pass to the curves of individual days, for none of the forms of the curves derived from means of observations can be detected in the curves for single days. Moreover, the character of the monthly curves (which, representing the longer series of observations, are the more authoritative) is not such as to indicate the existence of a diurnal period. The angularity of curves 8 and 9 cannot belong to a normal daily cycle, and must be referred to causes which, in their relation to the daily cycle, are accidental. And if the angular elements of Figures 10 and 11 were removed, the curves would approximate very closely to horizontal lines. The Mount Washington observations have therefore afforded no evidence of diurnal periodicity in the determination of altitudes.

If the reader will now compare together all the figures of Plate LVI he will see at once that they exhibit the most divergent characters. The curves of Strawberry Valley, of the Miesing, of Colfax, and of the Alps all represent indubitable, recurrent, diurnal variations, which cannot be ascribed to accident; but they have no single common element. The maximum of the Alpine curve corresponds approximately with the mini-

ma of the Miesing and Strawberry Valley curves. The Colfax and Alpine curves agree in making the evening result lower than the morning, but the Strawberry Valley curve makes it higher. The Lakeport curve and the Gold Run curve, which depend upon so few observations as not to be thoroughly established, agree in form with the Alpine curve, while the You Bet curve appears to be related to that of the Miesing. The Mount Washington curves, which rest upon longer series of observations than any of the others except the Colfax, have a smaller amplitude than any other, and are so indefinite and discrepant in their characteristics that they afford no comparative forms.

If these curves were accordant they would warrant the introduction of a diurnal factor in the thermic term of the formula, but their discordance serves to show that no such diurnal factor could be of universal application. The forms of the curves are evidently conditioned by some factor besides that of time, and it is highly probable that that factor is one of place. It is conceivable that an influence may be exerted by latitude, or by proximity to the ocean, or by the relation of the neighboring ocean to the prevailing winds, or by the aspect of the mountain slope—whether toward the rising or the setting sun—or by the approximation in altitude of the new station to the upper base on the one hand or to the lower on the other; but a comparison of the curves with the various data of locality fails to indicate that any such factor affords the key. It is conceivable also that the nature of the curve is determined by the modifications of the diurnal movements of the atmosphere wrought by the topographic peculiarities of the localities used as stations; and indeed this hypothesis appears to the writer more plausible than any other. It is a matter difficult to test, however, because, in the first place, there is no satisfactory theory of the diurnal movements of the air, and, in the second place, the relations of the various barometric stations to the surrounding topographic features are for the most part not recorded.

An altitude computed by the new formula depends upon the atmospheric pressures synchronously observed at three stations. At each station the pressure is subject to a daily cycle of change, and every variation from one hour to another tends to produce a corresponding variation in the computed altitude. The coincident variations at the three stations may be such as to neutralize each other in the computation, and in that case there is no actual variation in the computed altitude; but if they do not neutralize each other the computed altitude changes somewhat from hour to hour. The amount of this change depends strictly upon the three changes in atmospheric pressure, or, in mathematical phrase, the variation of computed altitude is a function of the variations of pressure at the three stations. If we conceive the diurnal pressure cycles of the three stations to be represented by curves, and the diurnal variation of computed altitude by another curve, then we may say that the curve of computed altitude is a function of

the three curves of pressure. If the three pressure curves sustain among themselves such harmonious relations that the combination of their elements produces for each hour the same determination of altitude, the curve of computed altitude becomes a straight line.

Whether or not, therefore, there is a diurnal variation in the coefficient of thermic density, the diurnal variations of computed altitude are intimately and inseparably associated with those of atmospheric pressure.

If we were in possession of the true theory of the diurnal curve of pressure, and if we understood the part which topographic surroundings play in the determination of the pressure curve of a station, we should be able to use this knowledge in the improvement of our hypsometric result; but it is by no means certain that we should in such case find it best to incorporate a diurnal factor in the formula. Any diurnal fluctuation which may affect the coefficient of thermic density must have its influence upon the pressure curves of the stations, but those pressure curves are at the same time the expressions of other influences which it is practically impossible to discriminate. It is therefore probable that the best method to diminish the errors dependent upon diurnal periodicity would be by applying corrections for diurnal variations of pressure directly to the barometer readings, after the manner of Williamson. Such corrections, if they could be efficiently applied, would eliminate *all* errors affected by a daily period, and would make their separate discrimination unimportant. The introduction of a diurnal factor in the thermic term of the formula might conceivably counteract the effect of diurnal fluctuations in the coefficient of thermic density, but would leave untouched the greater errors arising from local peculiarities of the daily movements of the atmosphere, and might even interfere with the elimination of those errors by means of corrections to the barometer readings.

We are led to conclude, therefore, that while calculations by the new formula are subject to errors which have a daily period, and while it may at some time be possible to reduce those errors by the application of corrections dependent upon topographic relations, it is nevertheless impracticable to improve the formula by the introduction of a diurnal term or factor.

The subject of the diurnal movements of the atmosphere, to which brief allusion is made in the preceding paragraph, is destined to occupy a no less important place in the future studies of meteorologists than it has occupied in the past; and notwithstanding its difficulty and complexity it is exceedingly attractive. At the risk of obscurity it has been given the smallest possible attention in this connection, because, notwithstanding its vital importance to precise hypsometry, its discussion at the present time can lead only to negative results. It is proper, however, by way of corollary, to call attention to the fact that the considerations invoked to account for the diurnal variations in hypsometric result by the new formula, involve an impeachment of one of the postulates of the formula. It is postulated by the new formula, as well as by all other

hyposometric formulas, that the difference between the observed air pressures at two stations expresses the weight of the differential air-column. If this were strictly true, the observed variations in the determined altitudes from hour to hour could only be due to corresponding changes in the coefficient of thermic density. Diurnal changes of thermic density must have a certain family resemblance in all localities; but, as we have seen, the diurnal curves of computed altitude have no family resemblance, and must therefore be referred, in part at least, to some other cause. Hence we are compelled to admit that our primary postulate is not strictly true, and that the column of air included between two stations may weigh something more or less than the differential column of mercury recorded by the two barometric readings. In a general way the explanation is a simple one. The air is daily heated by the sun, and is nightly cooled. The heating and the cooling cause expansion and contraction and therefore give rise to movements. These movements are resisted by the inertia of the air, and in the overcoming of this inertia there arise disturbances of the normal pressure. The observed diurnal changes of barometric pressure are due almost wholly to these disturbances. They are therefore dynamic in their nature; and they are beyond the reach of all existing hypsometric formulas, because it has been either tacitly or explicitly assumed in the construction of those formulas that the air is momentarily in a static condition.

The great advance that has been made in the dynamic study of the vortical or cyclonic movements of the air encourages the hope that a general theory of diurnal movements will soon be attained, but the day must be far distant when the part played by topographic features in the determination of diurnal movements will be so far understood that the knowledge will be of practicable service in hypsometry.

3. PROVISION FOR ANNUAL PERIODICITY.

We have now to consider the annual variation in the quantity of heat received from the sun, and to inquire whether there is a corresponding annual inequality of the density coefficient.

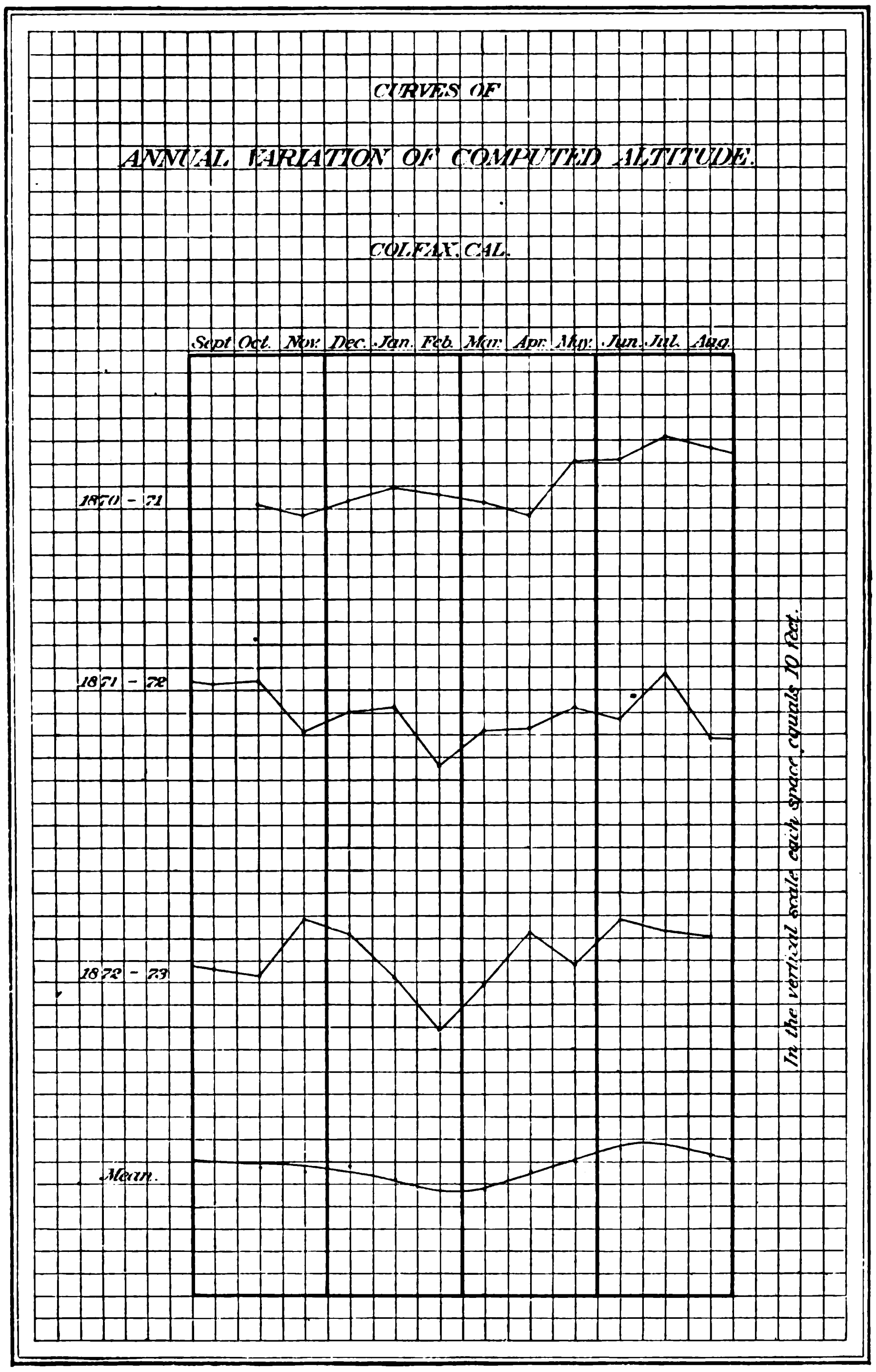
It will be recalled that the thermic term of the formula is intended to take account of an inequality in atmospheric density depending chiefly upon inequalities of temperature. These inequalities of temperature are produced by the sun, and their existence depends upon the fact that the principal heating of the atmosphere takes place in the stratum next the earth, while the compensatory cooling is by radiation from all its layers, high as well as low. The sun thus continually disturbs the equilibrium of temperature and density by making the lower layers abnormally warm and rare, and a vertical circulation is thereby produced which just as continually tends to restore the equilibrium. The coefficient of

thermic density at any moment is a result of, and an expression for, the excess of the solar influence over the compensatory influence of vertical circulation. It is *a priori* probable that the amount of this excess is greater at seasons when the solar influence is relatively great, and less at seasons when the solar influence is relatively small; or that the coefficient of thermic density is greater in summer than in winter.

If this be the fact, the constant D of the formula ought to be assigned different values at different seasons of the year, and it should be found that the application of the formula with a uniform value will give different results in different months. If the actual coefficient is greater in summer than in winter, it is evident that the use of its mean value for the entire year must afford a thermic correction too small in summer and too great in winter. Were we, therefore, with the formula as it stands, to compute the altitude of a well conditioned station at various seasons of the year, we should anticipate that our results in summer would be lower than our results in winter. If this anticipation were re-realized, and if a harmonious series of results were obtained from several localities, it would be possible to deduce from them a modification of the formula competent to take account of annual periodicity.

Unfortunately, there is no record of a suitable series of observations, and at present the annual variation of the coefficient can be neither established nor disproved. It will be instructive, however, to describe an attempt that was made to investigate it, because the result, although indecisive with reference to the point at issue, has nevertheless served to indicate the precautions necessary to be taken in order to reach a satisfactory conclusion.

The Californian observations published by Whitney extend over a period of thirty-five months and thus afford curves of computed altitude for three nearly complete years. The determinations of altitude for the individual months have already been given in Table XXIII, and the corresponding curves will be found in Plate LVII. The first three diagrams of the plate exhibit the variations for the individual years, and the fourth shows the monthly means for the entire period. In the fourth diagram the somewhat irregular line which would be produced by connecting the dots representing the determinations for individual months, has been replaced by a line of simple curvature, which probably expresses approximately the general law of variation. An inspection of the curves for individual years shows that the anomalous elements of the mean curve are due to inequalities which do not recur in each year, and may therefore be disregarded with propriety in a generalized expression. It thus appears that there is an actual annual periodicity in the determination of the altitude of Colfax, but it is almost the precise reverse of the one it seemed reasonable to expect as an expression of annual variation in the thermic constant. Theoretically, the determination of altitude should be least in summer, but practically it is greatest; theoretically it should be greatest in winter, but practically it is least


CURVES OF
ANNUAL VARIATION OF COMPUTED ALTITUDE.
COLFAX, CAL.
Sept Oct. Nov. Dec. Jan. Feb. Mar. Apr. May. Jun. Jul. Aug.
1870 - 71
1871 - 72
1872 - 73
Mean.
In the vertical scale each space equals 10 feet.

The assignment of the observed changes to variations in the coefficient of thermic density is therefore inadmissible, and an independent cause must be sought.

A possible cause, dependent upon the limitation of the observations at the several stations to three of the twenty-four hours, has already been suggested in another place (page 503), but the amplitude of the variation, which is indicated by the generalized curve to be approximately 20 feet, is too great to be accounted for in that manner.

Another and more satisfactory explanation is to be found in certain considerations dependent upon annual atmospheric gradient. The three stations of the Californian group are situated upon the long western slope of the Sierra Nevada, a great mountain range which on that side faces the Pacific Ocean. Its foot is indeed separated from the ocean by smaller ranges, but not in such way as to free its wind from maritime influences. It is a general fact that oceans are in summer cooler than the adjacent margins of continents, and in winter warmer than the same margins. These differences give rise to corresponding general atmospheric gradients which in summer are inclined toward the land, and in winter toward the ocean. It is therefore to be presumed that the general gradient between the highest and lowest Californian stations is in summer inclined toward the highest, and in winter toward the lowest. Assuming, for the sake of a standard, that the pressure at the lower station is normal, that at the upper is abnormally low in summer and abnormally high in winter. The same remark applies to the intermediate station, Colfax, but by reason of its smaller distance from the lower station the amount of its variation of pressure is less.

Affecting thus the relative pressures at the lowest and highest stations, the gradient affects the apparent weight and apparent height of the air column included between their levels; and in the same manner it affects the apparent height of the air column included between the lowest station and Colfax. These apparent heights are measured severally by the denominator and numerator of a fraction in the formula, and so long as they are affected in the same ratio the results given by the formula are unmodified. The apparent heights of the air columns are proportional to the real heights of the upper stations above Sacramento. The variations of pressure produced by gradient at the two upper stations we may assume to be proportional to their distances from Sacramento. If then the heights are proportional to the distances, the gradient cannot affect the computations; but if they are not proportional, an influence should be assigned to the gradient.

As a matter of fact, the distance of Colfax from Sacramento is something more than half the distance of Summit, while its altitude above Sacramento is only about one-third that of Summit. It results that the general gradients affect the estimated altitude of Colfax in greater ratio than they do the estimated altitude of the upper base, and thus exert a disturbing influence upon the computation of the altitude of

Colfax. The nature of this influence is to make the computed altitude of Colfax too high in summer and too low in winter.

Thus the theoretic influence of annual gradient is opposed to the theoretic influence of an annual variation of the co-efficient of thermic density, while it corresponds in character with the observed phenomena. We have no present means of judging whether it is quantitatively adequate to explain the phenomena, but recognizing it as a *vera causa* we are permitted to draw no conclusion in regard to the thermic density.

After the preceding paragraphs had been written, it was discovered that a group of stations belonging to the meteorologic system of India afforded data for the continuance of the inquiry. The figures are published in the official reports for the years 1875–1878, and exhibit monthly means for each year. The barometers were read four times daily, at the hours of 4 and 10, a. m. and p. m. The positions of the stations are given as follows:

Station.	North Latitude.	East Longitude.	Altitude.
	° ′	° ′	*Feet.*
Chakrata	30 40	77 55	7,051.58
Dehra	30 20	78 08	2,232.4
Roorkee	29 52	77 56	886.63

From which we deduce—

Stations.	Distance.	Difference in Altitude.
	Miles.	*Feet.*
Chakrata from Dehra	26	4,819.18
Chakrata from Roorkee	55	6,164.95
Dehra from Roorkee	34	1,345.77

It is recorded of Dehra and Roorkee that the altitudes of their barometers were determined by spirit level, and the conciseness with which the altitude of Chakrata is expressed probably indicates a like determination, although it is not so stated.

From these data the altitude of the intermediate station above the lowest was computed by the new formula for each of the forty-eight months, the vertical space between the extreme stations being assumed as a base line. The results appear in Table XXIX and are plotted upon Plate LVIII. The first four curves of the plate show the variations in the computed altitude from month to month for each of the four years of observation. The fifth curve is the mean of the four preceding. The sixth is a reproduction of the mean curve derived from the Californian observations,—introduced here for comparison.

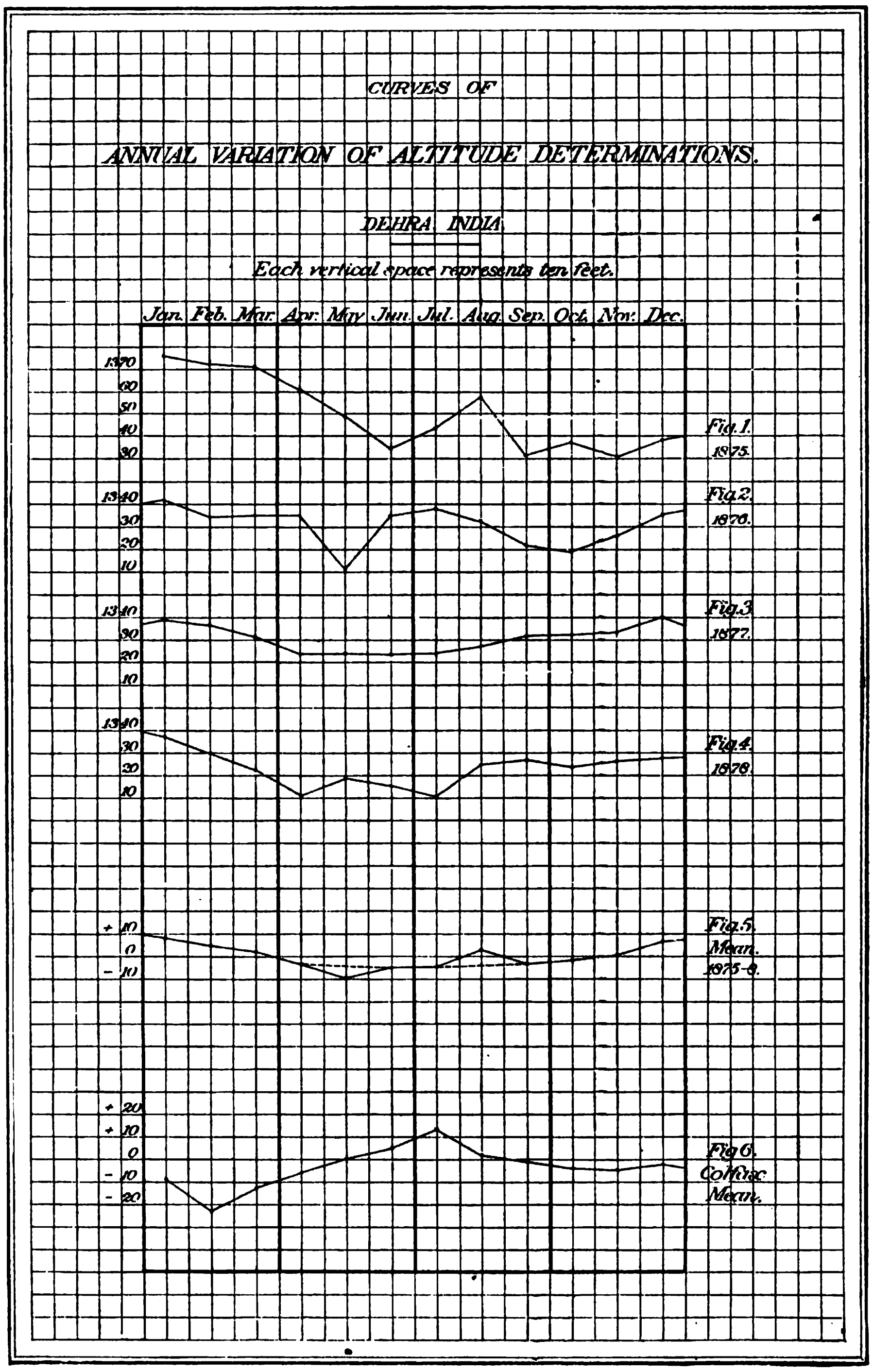

CURVES OF
ANNUAL VARIATION OF ALTITUDE DETERMINATIONS.
DEHRA, INDIA.
Each vertical space represents ten feet.
Jan. Feb. Mar. Apr. May. Jun. Jul. Aug. Sep. Oct. Nov. Dec.
Fig. 1. 1875.
Fig. 2. 1876.
Fig. 3. 1877.
Fig. 4. 1878.
Fig. 5. Mean. 1875-8.
Fig. 6. Co. Max. Mean.

TABLE XXIX.

Altitude of Dehra, India, above Roorkee, computed from Monthly Means; the Base Stations being Chakrata and Roorkee.

Month.	1875.	1876.	1877.	1878.	Mean of 4 Years.
	Feet.	*Feet.*	*Feet.*	*Feet.*	*Feet.*
January	1, 376	1, 342	1, 339	1, 337	1, 348. 5
February	1, 373	1, 335	1, 337	1, 330	1, 343. 7
March	1, 371	1, 335	1, 332	1, 323	1, 340. 2
April	1, 361	1, 335	1, 324	1, 312	1, 333. 0
May	1, 349	1, 312	1, 324	1, 319	1, 326. 0
June	1, 335	1, 336	1, 324	1, 316	1, 327. 7
July	1, 344	1, 338	1, 324	1, 311	1, 329. 2
August	1, 357	1, 333	1, 327	1, 325	1, 335. 5
September	1, 332	1, 322	1, 332	1, 327	1, 328. 2
October	1, 337	1, 319	1, 333	1, 324	1, 328. 2
November	1, 331	1, 326	1, 334	1, 327	1, 329. 5
December	1, 338	1, 335	1, 340	1, 328	1, 335. 2
Year	1, 350. 3	1, 330. 7	1, 330. 8	1, 323. 2	1, 333. 7

Considering, first, the mean curve (Figure 5), we see that it exhibits in August an aberrant element dependent upon an incongruous result appearing in the curve for 1875 and in no other; and we see, second, that it exhibits an aberrant element in May referrible to a still more incongruous determination shown by the curve for 1876. If we disregard the means for these two months, and draw the curve independently of them, as indicated by the dotted lines, we find it assuming a regular form with a single maximum and a single minimum. The maximum is relatively acute and occurs in midwinter; the minimum is broad and includes the entire summer. It therefore agrees in its essential features with the one theoretically anticipated, while it differs in every respect from the one derived from the Californian observations.

Comparing, now, the mean curve for the four years (Figure 5) with the curves for the individual years, we are able to detect its presence in the curves for 1877 and 1878, and less evidently in that for 1875, while the curve for the remaining year, 1876, betrays no trace of it. A system of corrections based upon it would plainly improve the harmony of the results in three of the four years, and would, on the whole, work to advantage.

The fact must not be overlooked, however, that the periodic variations expressed in this curve are of small magnitude as compared with the irregular variations exhibited by the same series of determinations. Even when the determinations are grouped by yearly means they exhibit inequalities greater than those with an annual period. The value of the altitude given by all the observations of 1875, collectively, is 21 feet greater than the values afforded by the years 1876 and 1877, and 28

feet greater than the value for 1878, while the amplitude of the curve of the annual change is only 13 feet. The application of corrections derived from the mean curve would therefore diminish the general irregularity in small ratio only.

It must be remembered, also, that the extreme stations of the group are separated by a horizontal distance of fifty-five miles—a space which admits the possibility of a large factor of annual gradient. It is true that in this case the ocean is not near; but the lowest station lies at the edge of an immense plain, while the highest is upon the slope of the loftiest mountain mass of the world, and such contrast of conditions can hardly fail to give rise to great periodic movements of the atmosphere. The relation of the vertical and horizontal interspaces of the stations is somewhat similar to that of the Californian group; the intermediate station is vertically nearer the lowest but horizontally nearer the highest.

On the whole, the question of the existence of a general annual period in the determination of hypsometric values by the new formula must be regarded as unanswered. The Californian and the Himalayan groups of stations give contradictory results; the former inconsistent with theoretic considerations, the latter consistent therewith. The Californian results are manifestly untrustworthy by reason of the proximity of the sea, but the trustworthiness of the Himalayan results is not assured. The question must remain open until a sufficient series of observations has been made at some properly conditioned group of stations. In such a group the horizontal distances should be small and the vertical great; the intermediate station should be approximately midway between the others; the observations should be equally distributed throughout the twenty-four hours, and for at least one year of the series they should be hourly; the locality should be inland.

It should be said by way of corollary that if the coefficient of thermic density changes with season, it should for the same reason change also with latitude and, in general, with local temperature. If, therefore, its variability shall at some time be recognized in the formula, it will be more logical to employ the general local temperature as its argument than to employ the season of year.

4. ADDITION OF A THIRD BASE STATION.

We shall now consider the possible advantage of increasing the number of base stations in the vertical series from two to three; and to make clear the bearing of such a change we shall recall the analysis of the subject of atmospheric density. The general law of the vertical distribution of density in the atmosphere is a function of Boyle's law of the relation of gaseous tensions to pressures, and is itself here called

the logarithmic law. It is simple in its nature and would need no qualification if the atmosphere were homogeneous in temperature and in moisture content. The modifying factor dependent upon moisture and temperature we have called the thermic density.

The thermic factor of density is divisible in thought into three parts, each of which requires consideration in the solution of the hypsometric problem. The first is its mean value, the second its law of vertical distribution, the third its rate of vertical change. The mean thermic density of any air column is known to vary from day to day and from hour to hour, and it is the especial object of the new hypsometric formula to determine its value in a given atmospheric column by means of a simultaneous measurement of its value in a similarly conditioned atmospheric column of known height. This is accomplished by the aid of two base stations, at each of which the pressure of the atmosphere is measured as a means of deducing the weight of the column between them.

The law of vertical distribution of the thermic density is not known, but the formula postulates for it a simple nature. It is probable that it, too, is subject to variation, and in another section the possibility of subjecting it to analysis and discussion will be considered.

The rate of vertical change of thermic density, or the rate at which the divergence of the actual density from the density indicated by the logarithmic law increases upward, is likewise known to be variable; but in the formula it is assumed to be constant, and its "constant" value finds expression in the denominator (D) of the thermic term. In the preceding sections the possibility of making provision in the formula for periodic changes of its value has been considered, but no reference has been made to non-periodic changes; yet a very brief consideration will suffice to show that it is liable to vicissitudes of as irregular a nature as those which affect any other atmospheric factor.

The vertical distribution of moisture and temperature is controlled primarily by the vertical circulation of the air, or rather by the relation of that circulation to the inequality of its heating by the sun. If the rate of vertical change were dependent upon that cause alone, it might be approximately equable, but it is really influenced by a variety of other factors, the most important of which is probably the horizontal circulation. The horizontal movements of the upper and lower strata of the atmosphere, at any locality, are frequently in different directions, and the movements of the upper strata are usually more rapid than those of the lower. The relations between the densities of high and low layers, so far as these are controlled by temperature and moisture, are therefore to a great extent independent of local conditions, and are liable to changes both abrupt and great whenever the winds change.

Every such change occasions a corresponding change in the rate of vertical increase of thermic density, and consequently in the actual value of the constant D. It would appear desirable then that some means be employed to ascertain the value of that constant in the field

of hypsometric work at the moment of barometric measurement. Our attempts to ascertain the *mean* value of the constant have been by computations based upon pressure observations at groups of three stations whose differences of altitude were known, and it appears perfectly feasible to ascertain its *momentary* value by the same method. To do so would require the establishment of an additional base station, so as to make the series consist of three bases instead of two, and as this would proportionately increase the expense of the hypsometric work, the consideration of economy demands that it shall first be shown to yield a compensatory advantage in precision.

The general principle upon which the new hypsometric method is based is that of determining the condition of the atmosphere at the moment of hypsometric measurement by means of a direct measurement of the density of a comparable column of known height. As the formula stands, only the mean density is determined by direct measurement. By the aid of a third base station, not only the mean density, but the rate of variation of the thermic density, would be measured.

It is easy to adapt the formula to this change. Assume that the new base station is placed intermediate in height between the upper and lower, and represent its barometer reading by i. Call the readings at the upper and lower base stations, as before, u and l, and that at the new station n. Represent by B the height of the upper base station, by b the height of the intermediate base station, and by A the height of the new station—all vertical distances being referred to the lower base station as an origin. Then, by the formula already developed,

$$A = B\,\frac{\log l - \log n}{\log l - \log u} + \frac{A(B - A)}{D} \quad . \quad . \quad . \quad (18)$$

and

$$b = B\,\frac{\log l - \log i}{\log l - \log u} + \frac{b(B - b)}{D} \quad . \quad . \quad . \quad . \quad (19)$$

From (19) we obtain

$$D = \frac{b(B - b)}{b - B\,\dfrac{\log l - \log i}{\log l - \log u}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (20)$$

in which all the quantities of the second member are known. Substituting in (18) the value of D given by (20), we have

$$A = B\,\frac{\log l - \log n}{\log l - \log u} + \frac{A(B - A)}{\dfrac{b\;(B - b)}{b - B\,\dfrac{\log l - \log i}{\log l - \log u}}} \quad . \quad . \quad (21)$$

an equation in which A only is unknown. B and b are, by postulate, known altitudes; and l, u, i, and n are observed barometric pressures.

If the law of the vertical distribution of thermic density were simple, or even if it were invariable, the application of this formula should give

results of the utmost uniformity; but it is evident that any disturbing causes, such as have been described, which induce abrupt changes in the *rate* of vertical variation, must also interrupt the vertical continuity of the *law* of distribution. It is not to be anticipated, therefore, that the application of the formula, even under the most favorable conditions, will eliminate all irregularities from hypsometric results. Theoretically, however, it should diminish those irregularities; and if it does so in any notable degree, there may be an economic advantage in the introduction of the third base station. The true test of the question is the practical one, and to this we now proceed by discussing the only available series of observations applicable to it.

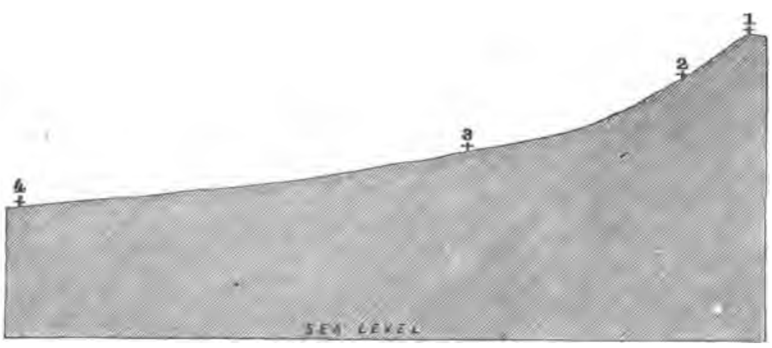


FIG. 30. Profile of the Western Face of Mount Washington, showing the Positions of the Meteorologic Stations in June, 1873.

The four stations upon the profile of Mount Washington have the relative positions indicated by the accompanying diagram. Station 1 is upon the summit; Station 2 is about 800 feet lower, and the descent to it is very steep; Stations 3 and 4 are so far down the valley which drains the mountain upon the west that they are somewhat shut in by spurs. They rest upon an easy slope, but nevertheless they are fairly upon the flank of the mountain, and the distance of the lowest from the summit is only three miles. For the purpose of comparison the altitude of Station 2 above Station 4 was first computed by reference to Stations 1 and 4 jointly, and second by reference to Stations 1, 3, and 4 jointly. The formula applied in the first case was that given in Equation (7), on page 442; in the second case, that given in Equation (21). Three series of computations were made. In the first series the means of the barometric pressures at the several stations for each day of the month of June, 1873, were used, each method affording thirty independent results, which are exhibited in full in Table XXX. For the second series the hourly means of the month's observations* were used, the results affording twenty-four comparisons. For the third series the individual hourly observations for the period of eight days, from June 22 to June 29, were used, affording one hundred and ninety-two comparisons. The second and third series

* See Table XXVIII.

of results are not here published in full, but are summarized in Table XXXI, from which it appears that whether the observations are taken individually, or by hourly means, or by daily means, the triple base yields a more uniform result than the double. The variation of the individual results among themselves appears to be reduced about 25 per cent by the use of the intermediate base station.

TABLE XXX.

Determinations of the Height of Station 2, Mount Washington, from Daily Means of Barometric Pressure.

Date.	Base Stations.			
	Stations 1 and 4.		Stations 1, 3, and 4.	
	Altitude.	Residual.	Altitude.	Residual.
	Feet.	*Feet.*	*Feet.*	*Feet.*
June 1	2,795.6	−23.1	2,819.7	+ 1.0
2	2,781.1	−37.6	2,796.2	−22.5
3	2,825.6	+ 6.9	2,826.2	+ 7.5
4	2,825.9	+ 7.2	2,836.5	+17.8
5	2,801.9	−16.8	2,814.8	− 3.9
6	2,827.1	+ 8.4	2,827.7	+ 9.0
7	2,819.7	+ 1.0	2,819.8	+ 1.1
8	2,835.9	+17.2	2,834.9	+16.2
9	2,831.3	+12.6	2,833.3	+14.6
10	2,831.2	+12.5	2,832.6	+13.9
11	2,813.9	− 4.8	2,828.1	+ 9.4
12	2,808.5	−10.2	2,816.1	− 2.6
13	2,830.2	+11.5	2,830.1	+11.4
14	2,839.4	+20.7	2,837.4	+18.7
15	2,825.5	+ 6.8	2,824.4	+ 5.7
16	2,826.2	+ 7.5	2,828.4	+ 9.7
17	2,769.8	−48.9	2,778.7	−40.0
18	2,800.9	−17.8	2,800.2	−18.5
19	2,812.0	− 6.7	2,815.8	− 2.9
20	2,797.9	−20.8	2,808.5	−10.2
21	2,792.5	−26.2	2,796.3	−22.4
22	2,822.7	+ 4.0	2,812.7	− 6.0
23	2,837.3	+18.6	2,818.9	+ 0.2
24	2,838.8	+20.1	2,823.2	+ 4.5
25	2,837.5	+18.8	2,820.9	+ 2.2
26	2,827.1	+ 8.4	2,817.6	− 1.1
27	2,814.9	− 3.8	2,809.6	− 9.1
28	2,814.3	− 4.4	2,808.6	−10.1
29	2,833.2	+14.5	2,816.0	− 2.7
30	2,839.5	+20.8	2,822.3	+ 3.6
Mean	2,818.6	14.6	2,818.5	9.9

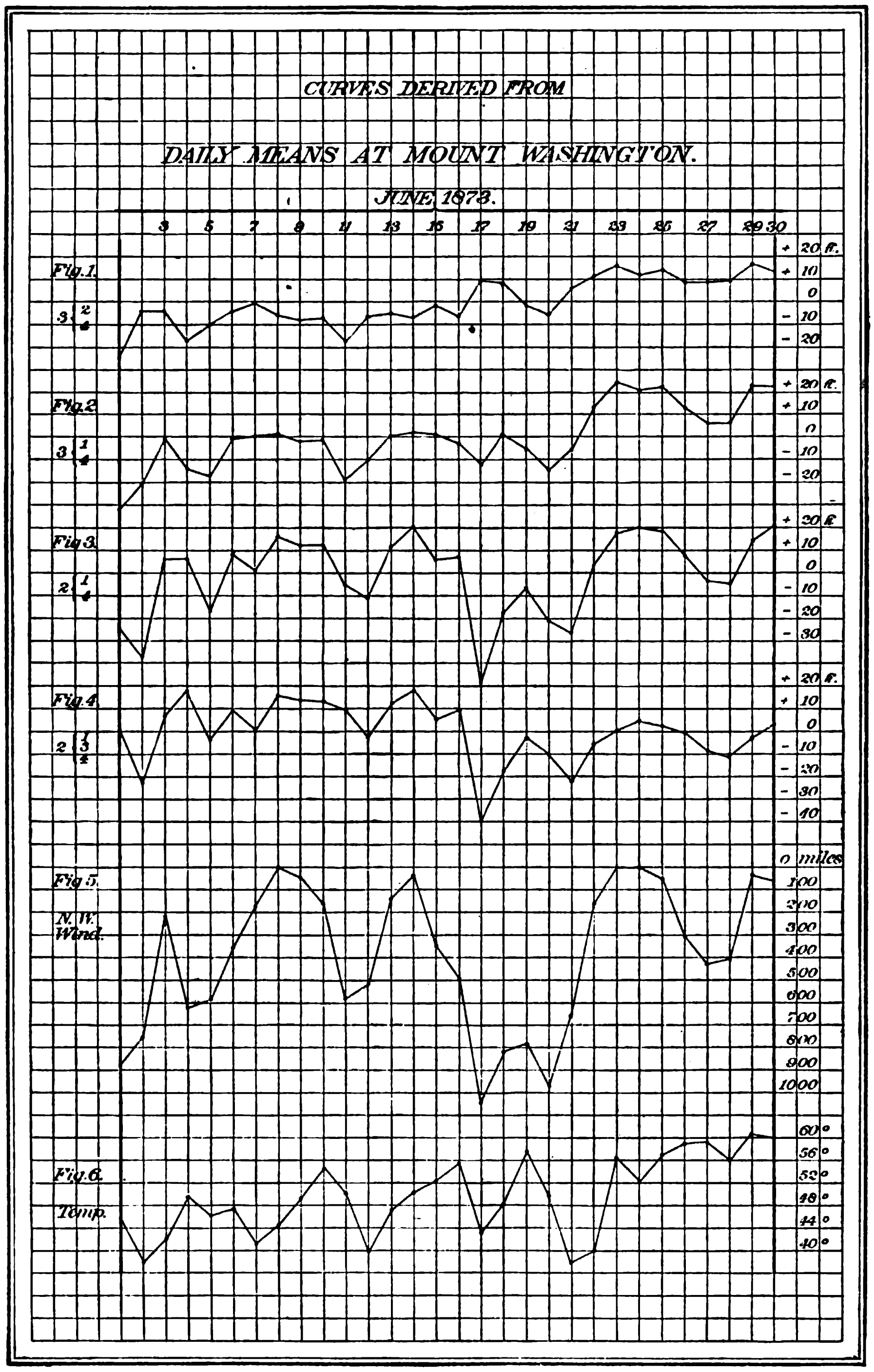

CURVES DERIVED FROM
DAILY MEANS AT MOUNT WASHINGTON.
JUNE, 1873.
Fig. 1.
Fig. 2.
Fig. 3.
Fig. 4.
Fig. 5.
N. W. Wind.
Fig. 6.
Temp.
miles

TABLE XXXI.

Comparing Mean Residuals of Determinations of the Height of Station 2, Mount Washington, by means of Two Bases and by means of Three Bases.

Observations.	Base Stations.		Ratio.
	Stations 1, 4.	Stations 1, 3, 4.	
	Feet.	*Feet.*	
30 daily means	14.6	9.9	100 : 68
Hourly means for the month of June	2.2	1.6	100 : 73
192 individual hours; June 23 to June 29	11.8	9.4	100 : 80
Mean			100 : 75

There is one feature of this table the appearance of which was not anticipated, and which has led the writer to extend the inquiry. It is a familiar general fact that the employment of means of observations in computations of this character diminishes the discordance of results, but in this particular case the determinations from thirty daily means are less accordant than the determinations from observations at the individual hours of the eight-day series. It would appear, therefore, that there is some disturbing factor which is subject to great variation from day to day and whose influence neither formula succeeds in eliminating; and it is manifestly important to our discussion that the nature of this factor be ascertained.

In Plate LIX various data derived from daily means of the month's observations are plotted, so as to exhibit their relations to the eye. The vertical lines indicate days and the horizontal lines for each of the upper four curves indicate computed altitudes, the space between each two consecutive lines representing ten feet. The curves therefore present the daily variations of computed altitude. In the computations affording the first curve the determined point was Station 3 and the base stations or reference points were Stations 2 and 4. In the case of Figure 2 the new station was the same, but the reference points were Stations 1 and 4. In the computations for Figures 3 and 4 the new station was Station 2, and the reference points were Stations 1 and 4 and Stations 1, 3, and 4, respectively. Figures 3 and 4 are plotted from the data contained in Table XXX.

An inspection of these curves shows, first, that they have a general similarity, differing chiefly in the magnitude of their undulations; and, second, that their most aberrant elements are minima, the maxima not ranging so far from the mean line. A comparison of the third curve, which was derived from a computation by means of two bases, with the fourth curve, which represents the same quantity derived from a computation by means of three bases, shows that the effect of the addition of the third base station was to diminish, but not remove, all the greater inequalities.

The curve exhibiting the least irregularity (Figure 1) is the only one derived independently of the observations at Station 1; and by this we are led to suspect that the influence of the disturbing factor is especially exhibited by the observations at that station. This suspicion is strengthened by a comparison of Figures 2 and 3, for the nature of the computations upon which they are based is such as to give a relatively small influence to the observations at Station 1 in the determination of the elements of Figure 2. In searching for the disturbing factor, we are therefore led to give especial attention to the observations made at the summit.

The published record of the observations gives for each of the four stations, not merely the barometric pressure, but the temperature and humidity of the air, the direction and velocity of the wind, the character and extent of the clouds, and the amount of precipitation; and thus enables us to compare our hypsometric variations with all the important meteoric factors. The curves of computed altitude were compared in turn, first, with the general humidity of the air; second, with the difference between the humidity observed on the summit and that observed at the lower station; third, with the rainfall; fourth, with the prevalence of clouds, and especially with the presence or absence of clouds enveloping the summit of the mountain; fifth, with the force of the wind, especially on Station 1; sixth, with the direction of the wind, especially on Station 1; seventh, with the temperature on Station 1; eighth, with the general temperature of all the stations; ninth, with the progressive rise and fall of the barometer; and tenth, with the difference between the atmospheric pressures on Station 1 and on Station 4. Among all these factors only two were found to exhibit any sympathy with the variations in computed altitude, the first being the general temperature and the second the wind.

The curve at the bottom of the plate (Figure 6) shows the oscillation of the mean temperature at the four stations, taken collectively, during the month,* and it is evident that there is a general correspondence of its maxima and minima with those of the most strongly marked curves of computed altitude. Whenever the hypsometric results were especially low the general temperature also appears to have been exceptionally low. Nevertheless, there appears no good reason to believe that the variations in the computed altitude were caused by the variations in temperature, for the only manner in which the temperature of the air can affect computations of altitude by the new formula is through differences of temperature between higher and lower layers of the air, and the records show that the differences of temperature between the highest and lowest stations of the series underwent far less change than the general temperature,—and, moreover, that its changes did not sympathize

* In the derivation of these means the observations for the entire twenty-four hours were not employed, but only those at 7 a. m., 2 p. m., and 9 p. m., that at 9 o'clock receiving double weight.

with the hypsometric variations. Our attention is therefore directed to the wind as the most probable source of the difficulty.

In the relation of the wind to the hypsometric results, not only force but direction and locality are concerned. That is to say, at one of the stations a great influence appears to have been exerted by wind in a certain direction—an influence proportioned to its strength—while winds from other directions had comparatively little influence. As will be shown in the sequel, the potent wind was that from the northwest (including also the north and west winds), and when that blew, all determinations of altitude involving the summit as a base station were comparatively low. Figure 5 of the plate exhibits for each day the total amount of wind reaching Station 1 from the northwest, expressed in miles, and a comparison with the curves above shows the close sympathy between the wind and the hypsometric results.

There are several different ways in which wind may be conceived to influence the computation of altitude. In the first place, it may by mere horizontal transfer give to the upper parts of the local atmospheric column an abnormal and incongruous temperature or degree of humidity. The winds upon the summit of Mount Washington are of great velocity as compared with those at the lower stations, and not unfrequently have a different direction, and it must often happen that they bring about changes in the condition of the upper strata of air which are not immediately shared by the lower. Nevertheless, when the record is scanned to ascertain the nature of these changes, it is found that in the case in question the cold air introduced from the northwest has very quickly brought the temperature of the valley into a normal relation with that at the summit, and that the differences in moisture, although they have frequently been considerable, have not been of such nature as to account for the variation of altitude determinations.

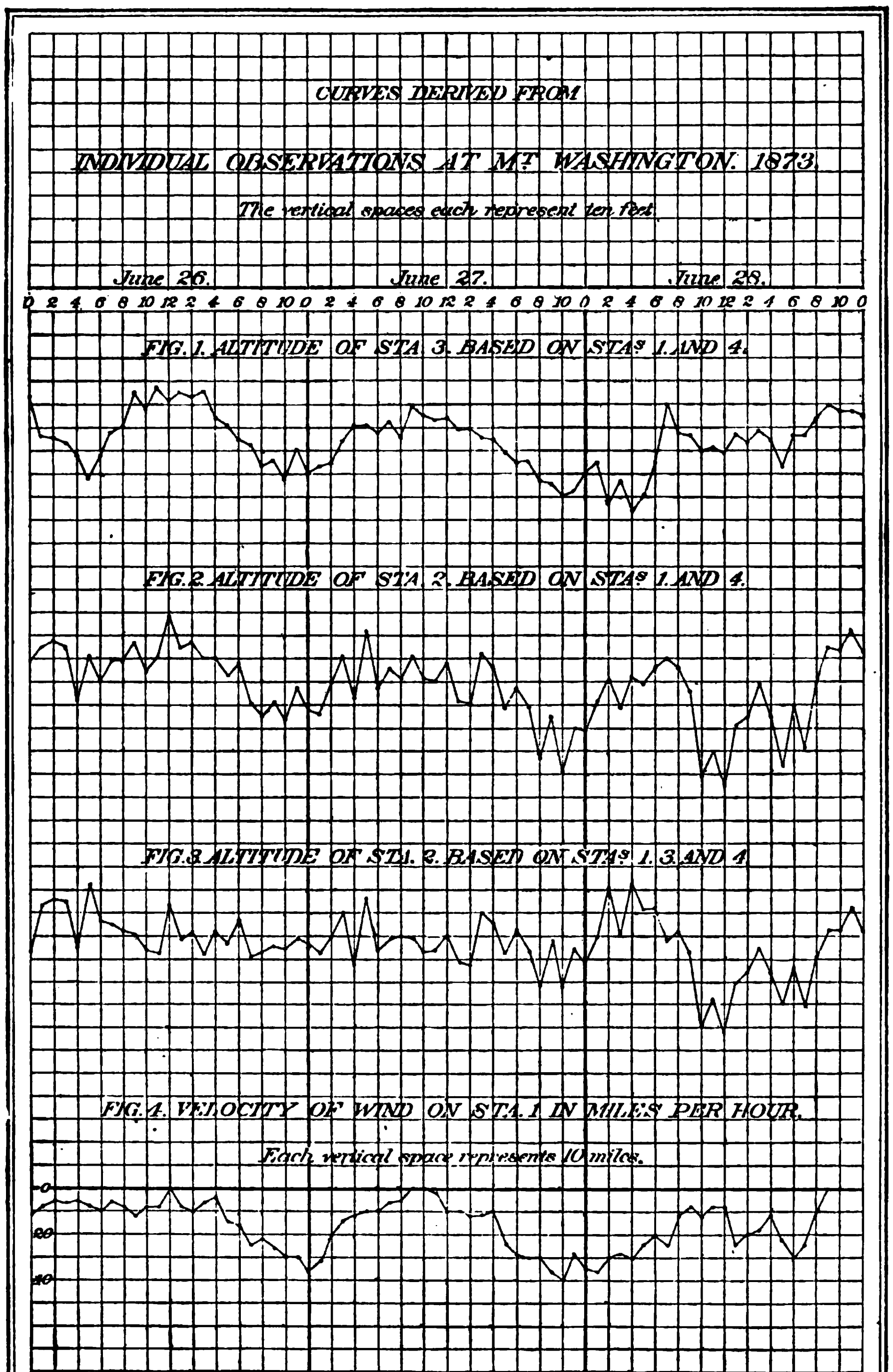
A second method of connecting winds with hypsometric inequalities is by means of gradients. The prevalence of a high wind upon the summit of the mountain, even though the valley at its base is possessed by a calm, is indicative of gradient; but the most rapid gradient it is possible to assign to it would amount to very little in the short space of three miles, and could not account for more than the tenth part of the observed discrepancies in computed altitude.

A third manner in which the wind might exert an influence, and the only manner in which its influence appears competent to produce the results, is by affecting the tension of the air in the observatory. It has already been pointed out that the wind tends to modify the tension of the air in every room to which it has access, rendering it abnormally great in some cases, and abnormally small in others, and that the effect produced in any particular room may vary with the direction of the wind. In the case of the Mount Washington observatory we do not know what the arrangement of the apertures was during the making of these observations, and even if we did know we might be unable to de-

termine deductively their influence upon the barometer; but we have reason to believe that such velocities of wind as were recorded by the observer are competent, under suitable conditions, to affect the barometer as it seems to have been affected, and we are therefore permitted, in the absence of other explanation, to ascribe the anomalies of the hypsometric results to errors wrought by the horizontal pressure of the wind in the observations of the vertical pressure of the atmosphere.

A further illustration of the same relation appears in Plate LX, where a series of altitude determinations from individual observations are compared with the simultaneous velocities of the wind upon the summit. The first and second curves show for three consecutive days the hourly variations in the determinations of the altitudes of Stations 2 and 3, referred to two base stations (1 and 4). The third curve shows the corresponding variation in the altitude of Station 2, as computed by the aid of three bases (1, 3, and 4). The fourth curve gives the recorded velocity of the wind at Station 1, in miles per hour, the direction of wind being continuously from the northwest. Not all the oscillations of the hypsometric curves reappear in the wind curve, but the greater number of them do.

These comparisons of curves, however, serve to do little more than illustrate the general relations of the phenomena. More precise conclusions have been reached by a series of classifications, to which we now proceed. The plotted wind curves refer to a single station only, but while that station experienced the strongest winds, the other three were yet subject to winds of greater or less force, and the inquiry would be incomplete if these were ignored. We have therefore classified the winds at each of the stations according to the magnitudes of the coincidently determined altitudes. For this purpose we have employed the series of determinations made from the hourly observations during the eight days from June 22 to June 29. The determinations of the altitude of Station 2 above Station 4 by reference to Stations 1 and 4 as bases, range from 2,775 feet to 2,859 feet. We have grouped these in four divisions, as indicated by the first column of Table XXXII, the first group embracing a range of 25 feet and the other three groups of 20 feet each. For each station we have taken from the published record the corresponding wind velocities at the three stations involved in the computation, and for each group we have added these velocities and obtained their arithmetic mean; the mean velocities appear in the third, fourth, and sixth columns of the table. A parallel series of computations, by which the altitude of Station 3 was derived from Stations 1 and 4 as bases, has been treated in the same manner, and the figures are arranged in the second division of the same table. A third series of computations, by which the altitude of Station 3 was deduced from Stations 2 and 4 as bases, has been similarly treated, and the results embodied in the third and lowest division of the same table.


CURVES DERIVED FROM
INDIVIDUAL OBSERVATIONS AT MT. WASHINGTON. 1873.
The vertical spaces each represent ten feet.
June 26.
June 27.
June 28.
0 2 4 6 8 10 12 2 4 6 8 10 0 2 4 6 8 10 12 2 4 6 8 10 0 2 4 6 8 10 12 2 4 6 8 10 0
FIG. 1. ALTITUDE OF STA. 3. BASED ON STAS. 1. AND 4.
FIG. 2. ALTITUDE OF STA. 2. BASED ON STAS. 1. AND 4.
FIG. 3. ALTITUDE OF STA. 2. BASED ON STAS. 1. 3. AND 4.
FIG. 4. VELOCITY OF WIND ON STA. 1 IN MILES PER HOUR.
Each vertical space represents 10 miles.
0
20
40

Inspecting the table, we note, first, that the mean wind at Station 3 and Station 4 was in all cases light, and that the numbers expressing it do not form progressive series as they stand in the table. As a matter of fact, the wind at those stations did not at any time during the eight days exceed ten miles per hour in velocity, and its influence upon the computations has in no wise been detected.

The wind at Station 1 attained a maximum velocity of forty miles per hour, and its mean velocities for the different groups of determined altitudes, as exhibited in the table, are not only of notable amount in some instances, but they form in each case a strongly characterized, progressive series, the strongest wind corresponding to the lowest determination of altitude, and *vice versa*. In the two cases here cited, Station 1 is regarded only as an upper base station, and the first and second divisions of the table agree in showing that the influence of wind at that station tends to diminish the dependent determinations of the altitudes of lower stations.

TABLE XXXII.

Velocities of Wind at Stations on Mount Washington, Arranged According to Corresponding Determinations of Altitude.

Altitude of Station 2, computed from Stations 1 and 4.	Number of Determinations	Mean Velocity of Wind, in Miles per Hour.			
		At Station 1.	At Station 2.	At Station 3.	At Station 4.
2775–99	9	20.9	19.4	....	3.9
2800–19	43	17.4	17.4	....	3.6
2820–39	108	5.9	9.4	....	3.4
2840–59	32	3 8	6.2	....	3.5
Station 3, computed from Stations 1 and 4.					
1210–29	10	28.3	....	2.6	2.7
1230–49	60	13.5	....	2.8	3.6
1250–69	117	4.7	....	2.8	3.5
1870–79	5	5.0	....	1.8	2.8
Station 3, computed from Stations 2 and 4.					
1210–29	4	....	15.7	2.2	2.0
1230–49	60	....	12.2	2.0	3.5
1250–69	127	....	10.1	3.2	3.5
1270–79	1	....	8.0	0.0	1.0

At Station 2 the maximum wind was thirty miles per hour, and the means, just as in the case of Station 1, form progressive series, the maximum velocities corresponding to low determinations of altitude and the minimum velocities to high. The sympathy of the wind with the altitude is less perfect in this case, however, than in the case of Station 1.

Moreover, while Station 2 is the upper base station in the case represented by the third example of the table, it plays the role of new station in the first example; and this difference of relation has an important bearing upon the interpretation of the figures. The barometer reading at Station 2 enters the computations in the two cases in such different ways that errors of the same nature have opposite influences upon the determinations of altitude. If, therefore, Station 2 as upper base station affords altitudes varying inversely with the force of the wind, as new station it should afford altitudes varying directly with the force of the wind. The indications of the two divisions of the table are therefore contradictory, and to harmonize them it seems necessary to assume that the more powerful winds upon Station 1 dominated in those computations involving both Station 1 and Station 2, and compelled the winds at Station 2 (usually sympathetic) to fall into the table in an order not truly representative of their influence in the computations. However this may be, the second and third cases exhibited by the table are preferable for the purpose of the investigation, because each includes only one station characterized by strong winds, and attention will be directed in the next procedure exclusively to them.

Having thus ascertained that the velocities of wind at Stations 1 and 2 are related to the magnitudes of altitudes determined by computations in which those stations enter as bases, and having reason to think that this relation is one of cause and effect, we now proceed to inquire how great effects are produced by winds of given velocities. For this purpose we reverse our previous process; first grouping the observations of wind according to velocities, and then determining the means of the corresponding computed altitudes. In the first case, winds were arranged according to computed altitudes; in the second, computed altitudes according to winds.

TABLE XXXIII.

Hourly Determinations of Altitude at Mount Washington for eight days in June, 1873, Arranged According to the Velocity of the Wind.

Velocity of Wind at Station 1, in miles per hour.	Altitude of Station 3, determined from Stations 1 and 4 as Bases.		Velocity of Wind at Station 2, in miles per hour.	Altitude of Station 3, determined from Stations 2 and 4 as Bases.	
	Number of Independent Determinations.	Mean Altitude.		Number of Independent Determinations.	Mean Altitude.
		Feet.			Feet.
0–5	96	1,254	0–5	46	1,252
6–15	60	1,251	6–15	97	1,254
16–25	19	1,248	16–25	43	1,248
26–35	13	1,231	26–30	6	1,249
36–40	4	1,228	....	....	....

Table XXXIII comprehends two divisions. In each the determined altitude is that of Station 3 above Station 4, but in the first the upper

base station is Station 1, while in the second it is Station 2. The first column in each division defines the groups of wind velocities at the upper station, the first group including all velocities from 0 to 5 miles per hour, and each succeeding group (except the last) including a range of 10 miles. The second column shows how many sets of observations fall within each group, and the third gives the means of the corresponding altitudes. The altitudes dependent upon the summit station as one of the bases exhibit a perfect sympathy with the velocity of the wind, forming a progressive series with a range of 26 feet. The altitudes dependent upon Station 2 exhibit a less perfect sympathy with the wind velocity and do not form a consistent series. Their range is 6 feet only, and they indicate that the influence of the wind is there very small. Nevertheless, the ways in which the barometer readings of Station 1 and Station 2 respectively enter into the computations of the altitude of Station 3 are such that the errors in the readings at Station 2 should have the greater influence. We are at liberty to conclude, therefore, that the element of locality enters largely into the influence of the force of wind upon the reading of the barometer, and that its influence was much greater upon the barometer read at the summit than upon that read at Station 2. In continuing the investigation for the purpose of learning more definitely the nature of the effect of the wind, we shall consequently restrict our attention to computations involving only Station 1, where the wind had greatest influence, and Stations 3 and 4, where its velocity was never great.

The next point to consider is the part played by the *direction* of the wind, for it has appeared by inspection of the record that some winds are more potent than others. In pursuance of this inquiry the hourly determinations of altitude for the eight June days were plotted upon section paper in such way that the horizontal scale represented heights and the vertical scale wind velocities. Each individual determination was indicated by a dot, and the color of each dot was made to show the corresponding direction of the wind. Displayed in this way, the determinations were seen to fall in two principal groups, the first of which included those associated with the north, northwest, and west winds, and the second those associated with the east, southeast, south, and southwest winds. The determinations corresponding to northeast winds were too few and too widely scattered to be confidently assigned to either group. A transcript from this plotting is given in Plate LXI, where the upper figure represents the northerly group and the lower the southerly. The determinations made during the existence of a calm appear in both figures, since the calm is the zero for all directions of wind. The vertical scale in each figure represents velocities of wind upon Station 1, in miles per hour; the horizontal scale represents computed altitudes, in feet, of Station 3 above Station 4.

The sympathy of the computed altitude with the velocity of north-

westerly winds is exhibited in Figure 1 by the drifting of the upper dots to the left and of the lower dots to the right, while the absence of this sympathy in the case of the remaining group of winds is shown by the fact that in Figure 2 no one of the higher dots falls without the horizontal range of the determinations corresponding to a calm.

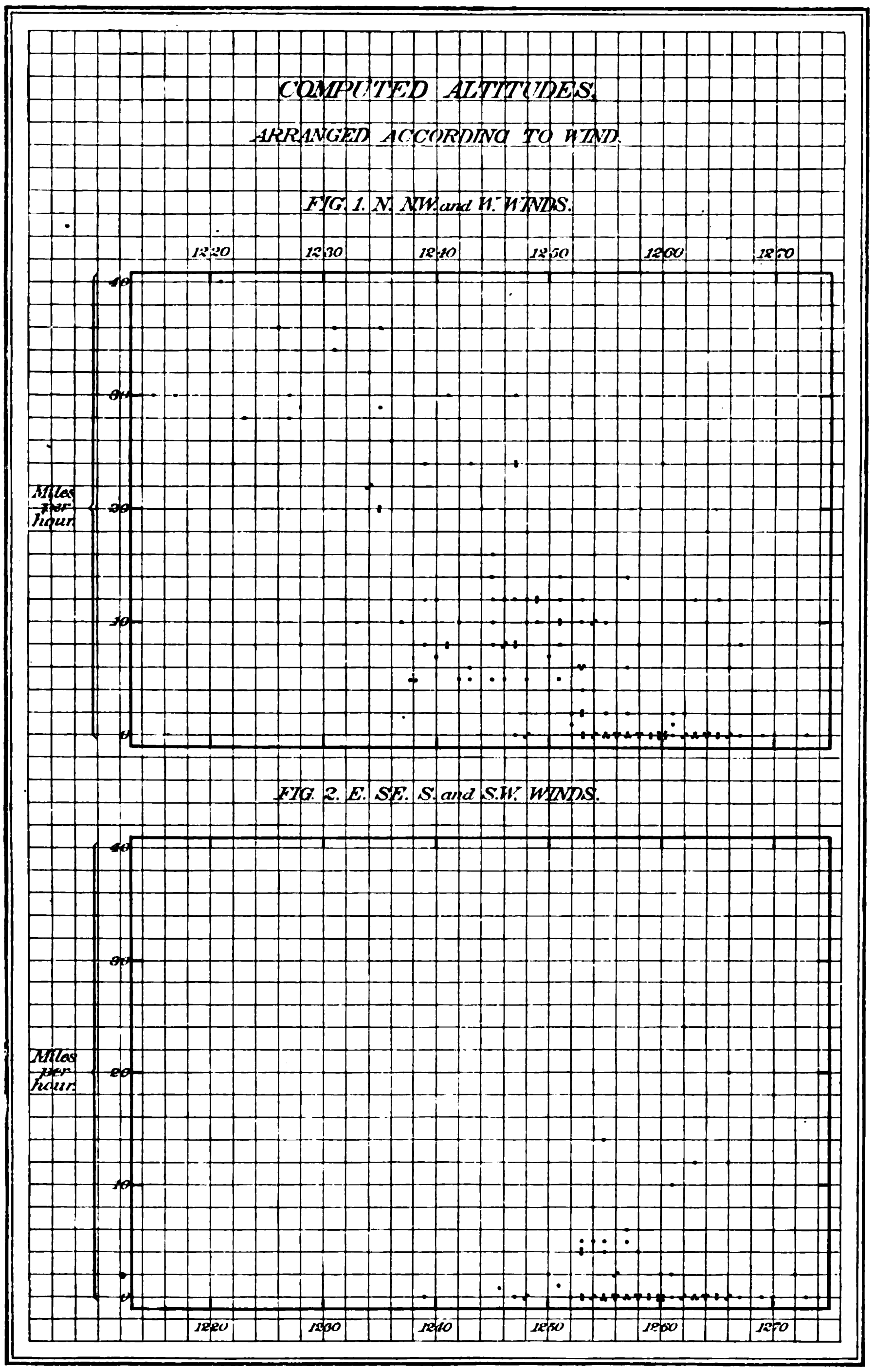
It happens, however, that during the eight days for which the hourly computations were made, there were no winds from the south or east comparable in force with the strongest winds from the northwest, so that the comparison exhibited by the plate is not entirely satisfactory. Indeed, the dots pertaining to the southerly group of winds really fall within the range of the dots pertaining to the northwesterly, and they are so few in number that the direction of their drift cannot be confidently asserted. To secure a more definite result a few additional computations were made, and the data for Table XXXIV were assembled.

TABLE XXXIV.

Relation of Computed Altitudes of Station 3, on Mount Washington, to the Direction of Wind at Station 1.

	Wind with Velocity of 20–30 Miles per Hour, from the—		No Wind.			
	N. W.	S. W.				
			1,273	1,262	1,259	1,255
			1,272	1,263	1,258	1,255
			1,270	1,261	1,258	1,254
Computed Altitudes.	*Feet.*	*Feet.*	1,269	1,261	1,258	1,254
	1,260	1,267	1,267	1,261	1,258	1,253
	1,258	1,266	1,266	1,261	1,257	1,253
	1,247	1,265	1,266	1,260	1,257	1,253
	1,244	1,262	1,265	1,260	1,257	1,253
	1,243	1,259	1,265	1,260	1,257	1,252
	1,239	1,257	1,264	1,260	1,257	1,252
	1,236	1,255	1,264	1,260	1,256	1,252
	1,235	1,254	1,264	1,260	1,256	1,251
	1,235	1,252	1,264	1,260	1,256	1,250
	1,234	1,249	1,263	1,259	1,256	1,248
	1,234	1,249	1,263	1,259	1,256	1,248
	1,228	1,249	1,263	1,259	1,255	1,248
	1,227	1,241	1,262	1,259	1,255	1,247
	1,221					1,246
Mean..	1,239±2	1,256±2	1,258.5±0.5			

The first column contains heights selected from the eight-day series of determinations, and includes all the values of the altitude of Station 3 determined during the prevalence on Station 1 of a wind from the northwest with a velocity from 20 to 30 miles per hour. To obtain the corresponding quantities in the second column the entire record for the month was searched, and a similar computation of altitude was made for each hour at which the wind upon Station 1 was from the southwest and had a velocity of 20 to 30 miles. The third column, which is divided on account of its length into four parts, contains all those determina-


COMPUTED ALTITUDES.
ARRANGED ACCORDING TO WIND.
FIG. 1. N. NW. and W. WINDS.
1220
1230
1240
1250
1260
1270
40
30
20
10
0
Miles per hour
FIG. 2. E. SE. S. and S.W. WINDS.
40
30
20
10
0
Miles per hour
1220
1230
1240
1250
1260
1270

tions of the eight-day series made when the wind on Station 1 did not exceed 2 miles per hour. The first column represents, by 14 examples, the effect of a 25-mile wind from the northwest; the second column, by 13 examples, the effect of a 25-mile wind from the southwest; the third column, by 69 examples, the influence of a calm. For facility of comparison the numbers in each column are arranged in numerical order. Comparing first the northwest wind with the calm, it will be perceived that the mean of the determinations affected by the former is 19½ feet less than the mean of the determinations affected by the latter. That this difference is not accidental is attested, first, by the fact that the probable errors of the two determinations are comparatively very small, and, second, by the fact that the two series of numbers do not greatly overlap. Only a single determination with northwest wind is greater than the mean of those with no wind, and there is no determination of the no-wind series so small as the mean of those with northwest wind. The influence of the northwest wind is therefore clearly revealed.

Comparing now the southwest wind with the calm, we find that the means of the two corresponding series of determinations differ from each other by 2½ feet only, an amount which is accounted for by their probable errors—that is to say, the determinations approach each other within the range of their uncertainties. We cannot affirm, therefore, that the southwest wind exerts any influence upon the determination of altitude. If it does exert any it certainly is slight as compared with that of the northwest wind.

We need not extend the comparison, for the precise influence of individual winds at the given station at the given time is not a matter of present importance. It is sufficient to have established the fact that not all winds exerted the same influence, but that direction, as well as velocity, was concerned in the perturbations of the barometer.

Having ascertained that the observations at Station 1 were more influenced by wind than those at Station 2, and that the northwest was one of the more potent winds at Station 1, we now proceed to seek a quantitative expression for the influence of that wind. For this purpose it is desirable to contrast the strongest winds with a calm. The record for the entire month has accordingly been searched and two series have been selected, the first characterized by winds with velocities from 50 to 56 miles per hour, the second by winds with velocities from 60 to 68 miles. The first series numbers ten, the second seven. For each hour of each series the altitude of Station 3 has been computed, as in the last example; and the resulting determinations will be found in the second and third columns of Table XXXV. The first column of the table repeats from the preceding table the numbers corresponding to a calm.

TABLE XXXV.

Relation of Computed Altitudes of Station 3, Mount Washington, to the Velocity of the Northwest Wind at Station 1.

	Reported Velocity of Wind, in Miles per Hour.								
	0 to 2.							50 to 56.	60 to 68.
Computed Altitudes.	1,273	1,264	1,261	1,259	1,257	1,255	1,252	1,234	1,218
	1,272	1,264	1,261	1,259	1,257	1,255	1,252	1,231	1,216
	1,270	1,264	1,261	1,259	1,257	1,255	1,251	1,230	1,214
	1,269	1,263	1,260	1,259	1,257	1,254	1,250	1,229	1,207
	1,267	1,263	1,260	1,259	1,256	1,254	1,248	1,226	1,205
	1,266	1,263	1,260	1,258	1,256	1,253	1,248	1,226	1,192
	1,266	1,262	1,260	1,258	1,256	1,253	1,248	1,225	1,185
	1,265	1,262	1,260	1,258	1,256	1,253	1,247	1,223	
	1,265	1,262	1,260	1,258	1,256	1,253	1,246	1,223	
	1,264	1,261	1,260	1,257	1,255	1,252		1,221	
Mean.	1,258.5±0.5							1,226.8±0.8	1,205.8±3.2

The series of numbers in the three columns are mutually exclusive. The altitudes computed during a calm, range from 1,273 to 1,246 feet; those during the prevalence of a 50-mile wind, from 1,234 to 1,221; those during the prevalence of a 60-mile wind, from 1,218 to 1,185. This phenomenon cannot be referred to temporary conditions or other accidents. The observations represented by the first series are scattered through eight days; those affording the 50-mile series of altitudes, through a period of five days. Only the observations for the 60-mile series are grouped closely together in the record.

The same mutual exclusiveness is indicated by the probable errors of the means, which it will be seen are very small as compared to the differences between the means. The mean altitude determination affected by the 50-mile winds is 31.7 feet smaller than that affected by a calm, and the probable error of this difference is only ± 1 foot; while that associated with the 60-mile winds is 53.2 feet smaller, with a probable error of ± 3.2 feet.

It remains to compare the dynamic equivalents of these errors in computed altitude with the pressures of the corresponding winds, and to accomplish this we shall estimate each in terms of the mercurial inch.

The measurement of the wind on Mount Washington was made by means of a cup-anemometer, an instrument recording the velocity of a set of cups revolved by the wind. Theoretically, the velocity of the wind is three times that of the cups, and in the velocities reported by the Signal Service the factor 3 was used in the reduction. It has been more recently ascertained by Dohrandt, however, that in practice the revolution of the cups is more rapid, and that the proper factor for such an instrument as that used on Mount Washington is 2.4 instead of 3*.

* Repertorium für Meteorologie. Memoir No. 5, 1878. Bestimmung der Anemometer-Constanten, von F. Dohrandt.

The recorded velocities are therefore too great and need to be reduced twenty per cent. After making this allowance, the mean velocity of wind corresponding to the second column of Table XXXV is found to be 41.6, and that corresponding to the third column 50.2 miles. The equivalent pressures, expressed in inches of the mercurial column, are .122 and .177. These numbers appear in Table XXXVI.

Assuming, as we certainly are warranted to do, that the synchronous variations in the computed altitude of Station 3 are due to perturbations of the barometer at Station 1, we proceed to ascertain the nature and amount of those perturbations. It is needless to detail the computation, which can be readily inferred from the part played by the pressure at Station 1 in the computation of altitude. Suffice it to say that the change in the barometric pressure at Station 1 necessary to produce the observed variation in the determined altitude of Station 3 is .078 inch in the case of the weaker wind and .132 inch in the case of the stronger. The nature of this change is a depression—that is to say, in order to account for the diminution in the computed altitude we must assume that the barometer was relatively low during the prevalence of the stronger winds. The effect of the wind was therefore to diminish the tension in the observatory at Station 1, and not to increase it.

Comparing now the deduced depression of the barometer with the coincident pressure of the wind, we find that it approaches the latter in amount but does not equal it. In the case of the less violent wind, the barometric depression is 64 per cent of the barometric column expressing the force of the wind, and in the case of the more violent it is 75 per cent. (See Table XXXVI.)

TABLE XXXVI.

Comparison of the Pressures of High Northwest Winds on Mount Washington with the Coincident Depressions of the Barometer.

	Series I.	Series II.	Series III.
Number of observations	69	10	7
Mean velocity of wind (recorded) in miles per hour	0	52.0	62.7
Mean velocity of wind (deduced) in miles per hour	0	41.6	50.2
Pressure of wind, expressed in barometric inches....(A)	0	.122	.177
Computed altitude of Station 3 (mean), in feet	1258.5±0.5	1226.8±0.8	1205.3±3.2
Error in computed altitude caused by wind, in feet	0	−31.7	−53.2
Equivalent depression of barometer on Station 1......(B)	0	.078	.132
Ratio of barometric depression (B) to synchronous pressure of wind (A)	....	.64	.75

It has been shown by Hagemann by a series of ingenious experiments that the power of suction exerted by the wind in blowing over an aperture approximates closely, under favorable conditions, to the force of the wind; and there appears warrant for his conclusion that the quantitative

limit to its exhausting power is equal to its horizontal pressure.* We may therefore conclude that in referring the hypsometric error under consideration to the local influence of wind upon the tension of the air in the observatory, we are appealing to a cause which is quantitatively sufficient, and our demonstration is thus rendered as complete as it could be without actually visiting the observatory and examining and experimenting upon its apertures. This indeed is impracticable, first, because the observatory now in use upon Mount Washington is not the one used during the month of June, 1873, and, second, because the records of the Signal Office fail to show precisely what building was occupied at that time. It is probable, however, that the building actually used stood upon the northwest side of the absolute summit of the mountain, so that of the winds rushing past it those from the northwest had an upward tendency, while some others had not. During the prevalence of a high wind there can be little doubt that the principal opening in the building was the chimney, and if the orifice of that was turned upward, a strong draft would be created by a wind tending obliquely upward. There is a fair presumption, therefore, that the northwest winds communicated their influence to the barometer of the observatory by means of the draft of the chimney.

The result of our inquiry was not in the least anticipated, but it is none the less valuable. It gives us an additional reason for assigning a low weight to all hypsometric determinations made by means of the barometer during the prevalence of a high wind, and it directs attention to the importance of devising means for the elimination of this particular wind influence, not only from the data for hypsometry, but from meteorologic data in general. The discussion of such corrective means would be out of place here, since it pertains in no wise to the new hypsometric method, but a brief consideration will be given to it in a note at the end of the paper.

The facility afforded by the new formula in the discussion of series of observations, and the fact that it has here led to the detection of a systematic error of observation, testify to the soundness of the principles upon which it is founded and encourage the belief that it will find a sphere of usefulness outside its special hypsometric province.

We now return to the main subject of this section—the consideration of the possible advantage to be gained by increasing the number of base stations from two to three. Having learned that the observations previously used to test the matter were to a certain extent vitiated by the local influence of winds, we now repeat the test with the aid of a selected series of well conditioned observations. In the first place, we reject from the eight-day series in June all those hours at which the wind at any one of the four stations equaled or exceeded a velocity of ten miles per hour; and from the observations made at the remaining

* Annuaire pour l'année 1876 de l'Institut Meteorologique Danois. "Sur les anemometres," par G. A. Hagemann.

74 hours compute the height of Station 2 by the method with a double base, and again by the method with a triple base. The rejection of the observations dominated by wind increases the mean of the determinations of height from 2,828 feet to 2,836 feet, and it diminishes the average deviation of individual determinations by the aid of two base stations from 11.8 to 7.7 feet. It diminishes also the average deviation of determinations by the aid of three bases from 9.4 feet to 7.8 feet. It therefore improves the harmony among themselves of the individual determinations by either method; but it removes at the same time the apparent advantage of the method with three bases, for the selected observations give no better result with three bases than with two.

TABLE XXXVII.

Altitude Determinations on Mount Washington, from Individual Observations made when the Velocity of Wind was Less than Ten Miles per Hour.

Method of Computation.	Height of Station 2 above Station 4; Mean of 74 Determinations.	Average Deviation of individual Determinations from Mean.
	Feet.	*Feet.*
By Double Base (Stations 1 and 4)	2835.5	7.7
By Triple Base (Stations 1, 3, and 4)	2836.2	7.8

To continue the comparison, a selection has been made from the thirty days of June, 1873, of those ten days on which the wind at Station 1 on Mount Washington was least, and the altitude of Station 2 was computed by the two methods for those days. The results are displayed in Table XXXVIII, and are still less favorable to the triple base, the mean residual being increased by its use from 4.9 to 6.5.

TABLE XXXVIII.

Altitude Determinations at Mount Washington from Daily Means of Pressure Observations. The Ten Days of June, 1873, exhibiting the Lowest Mean Velocity of Wind.

Date.	Height of Station 2 above Station 4, computed from—			
	Stations 1 and 4.		Stations 1, 3, and 4.	
	Altitude.	Residual.	Altitude.	Residual.
	Feet.	*Feet.*	*Feet.*	*Feet.*
June 3	2,825.6	− 6.7	2,834.8	+ 2.6
9	2,831.3	− 1.0	2,841.9	+ 9.7
13	2,830.2	− 2.1	2,838.7	+ 6.5
14	2,839.4	+ 7.1	2,846.0	+ 13.8
22	2,822.6	− 9.7	2,821.2	− 11.0
23	2,837.3	+ 5.0	2,827.5	− 4.7
24	2,838.8	+ 6.5	2,831.8	− 0.4
25	2,837.5	+ 5.2	2,829.5	− 2.7
26	2,827.1	− 5.2	2,826.2	− 6.0
29	2,833.2	+ 0.9	2,824.6	− 7.6
Mean	2,832.3	4.9	2,832.2	6.5

These two tests are indeed inconclusive, by reason of the brevity of the series of observations upon which they are based, but they serve to suggest that the error which in the first group of tests appeared to have been eliminated by the introduction of the third base, may have been, in whole or in part, that caused by the pressure of the wind; and they certainly give no warrant for the belief that with properly conditioned observations the employment of three base stations will afford a higher degree of precision than the employment of two. It should be said, however, that the Mount Washington series of observations, although the best available for the discussion of this question, are not the best conceivable, and it is not impossible that a more exhaustive treatment of the subject may at some future time vindicate the utility of the triple base.

5. BETTER FORM FOR THERMIC TERM.

In the construction of the new hypsometric formula, it was postulated that the vertical change of density dependent upon temperature and moisture is uniform at all altitudes, but we have no reason to believe that this assumed law of distribution is true. Indeed, we are assured that it does not obtain in any specific case, so that it is only in general averages that it can possibly represent the actual facts.

There are no present means of testing it, but it is easy to project a system of observations which would serve to illuminate the subject. If a string of meteorologic stations, as many as five in number, were established upon a steep mountain slope in such way that their local conditions were closely similar except in the matter of altitude, while their altitudes formed a uniform series, the discussion of their observations would accomplish the desired result. The pressure differences of the successive stations, taken in connection with the known differences of altitude, would afford the densities of the several segments of the total atmospheric column, and would enable the law of their succession to be developed.

The same string of stations would serve to determine the constant of the formula and would afford material for the satisfactory discussion of diurnal and annual periodicity in hypsometry by the new method.

If the essential incompetence of the postulated law of density variation were demonstrated by such an investigation, it would become necessary to give a different form to the thermic term of the formula, but at present there appears no ground for the suggestion of a change.

6. GENERAL PROVISION FOR NON-PERIODIC GRADIENT.

The atmospheric inequalities affecting barometric hypsometry may be broadly classified as vertical and horizontal. The vertical inequali-

ties, or the variations of density in the local vertical column, are the sole objects of consideration alike in the new hypsometric method and in what we have called the ordinary and the empiric methods. The horizontal inequalities, which consist chiefly of gradients,—annual, perennial, and non-periodic or cyclonic,—are not considered by any formula in use. The only manner in which hypsometry practically attempts to avoid their influence is by using the means of long series of observations, and the advantages of this procedure cannot be reaped by ordinary geographic surveys, which are unable to make a great number of observations, or even more than a single observation, at each new station. The only general device adapted to the use of the geographer is the one deriving corrections for gradient errors by means of plotted isobars, and this involves the employment of so many auxiliary base stations that it can rarely, if ever, be employed with economy when the entire expense of the stations has to be borne by the geographic work. The great development of meteorologic work, however, which has followed and is following the success of meteorologists in the prediction of storms, promises to afford the geographer, in many places, and at no distant day, the data necessary for the determination of gradients; and it is pertinent to inquire how he can employ them to the best advantage.

It is quite conceivable that a comprehensive formula could be devised in which every observed element affecting the determination of altitude would find place, and through which the result would be evolved by a single complex process; but it is probably better, as it certainly is simpler, to treat the vertical and horizontal factors separately. In the judgment of the writer the vertical factor should be treated by a hypsometric formula, properly speaking, whether that of the new method or of the ordinary; but before this is done the horizontal factor should be treated for the purpose of correcting the barometric data intended for use in the hypsometric computation.

It is desirable that the stations used in determining gradient do not differ greatly among themselves in altitude. Let us first suppose them to have the same altitude, and let us further suppose (assuming the use of the new method) that they include among their number one of the base stations of the hypsometric pair. To ascertain the gradients at any moment we have merely to subtract the barometer reading at the hypsometric base station from each of the simultaneous readings at the auxiliary stations, and we obtain in the remainders the relative gradients of the several auxiliary stations. Plotting these upon a map we are enabled to draw lines of equal gradient (isobars) referred to the hypsometric base station as a zero. The relative gradient of the new station is then seen by reference to the position of the station on the map, and its amount, applied with the proper sign as a correction to the reading, prepares the latter for use in the hypsometric formula.

Let us now suppose that the auxiliary stations, as would usually occur, differ somewhat in altitude from the hypsometric base station

with which they are compared, and that these differences are known. The relative gradient cannot now be ascertained by simple subtraction, but must be reached by a computation involving an allowance for the density of the atmosphere. Assuming that the density conditions are similar throughout the entire district, the principles upon which the new formula is based readily afford the means of making this computation.

Assume, for convenience, that that base station of the hypsometric pair which approximates in height to the auxiliary stations is the lower of the two. Represent by G the relative gradient of an auxiliary station, by h the reading of the barometer at that station, and by H the same reading after correction for gradient.

$$G=h-H.$$

Then, by the formula,—Equation (7)—

$$A=B\frac{\log l-\log H}{\log l-\log u}+\frac{A\ (B-A)}{D}$$

whence, by transformation—

$$H=\log^{-1}\left[\log l-\frac{AD-A\ (B-A)}{BD}(\log l-\log u)\right]$$

and by substitution—

$$G=h-\log^{-1}\left[\log l-\frac{AD-A\ (B-A)}{BD}(\log l-\log u)\right] \quad ..\ (22)$$

In this equation, B is the known difference in altitude between the hypsometric pair of bases, and A is the known difference in altitude between the lower base station and one of the auxiliary bases. The expression $\frac{AD-A\ (B-A)}{BD}$ is therefore constant for each auxiliary base; and in each specific case the gradient (G) is a function merely of the simultaneous barometer readings at the upper and lower base stations and at the auxiliary station. When the number of observations is great, the labor involved in the computation of the second term of the second member (H) can be abridged by the construction of a simple table.

The relative gradients of the various auxiliary stations having been thus derived, the procedure is the same as in the preceding case.

Of the practical value of the plan here proposed for determining the gradient errors of the barometer readings at the auxiliary stations, the writer is unable to judge. Like every other hypsometric device, its utility can only be demonstrated by the practical test; and like every other device, it is liable to encounter practical difficulties which cannot be foreseen. It is here developed, merely as the logical consequence of the general principle underlying the new formula—the principle which warrants the determination of the density of a column of air by a direct measurement of the density of a neighboring column of known height.

It is the belief of the writer that the perfect elimination of the influence of cyclonic gradients from hypsometry is impossible, for the reason that different systems of gradient exist simultaneously at different altitudes. However thoroughly the system of gradients in a given horizontal plane may be determined, there seems no possible method by which to deduce from it the gradient system of a higher plane, and unless this can be done a considerable element of error must always remain.

The satisfactory determination of the systems of gradient which succeed each other in mountainous districts is an unsolved problem in meteorology to which a great deal of attention has been devoted. The formula embodied in equation (22) is adapted, so far as form goes, to its solution, but there is no immediate opportunity to test it, and in the face of so many failures it would be rash to anticipate its practical success. It is barely possible, however, that it may afford trustworthy results in a somewhat larger field than that to which hypsometry would assign it,—that it may find a meteorologic as well as a hypsometric use.

7. SPECIAL PROVISION FOR NON-PERIODIC GRADIENT.

There is a special case, arising not unfrequently in geographic work, in which it is possible to escape a large gradient error by the aid of a single outlying base station. Let us suppose that a pair of hypsometric base stations (U L of the diagram) are in use, and that by their aid the altitudes of new stations in their vicinity are being determined. Let us suppose, further, that a second piece of geographic work is in progress, which demands the measuring of the altitudes of a group of new stations in the locality S N—so remote from the pair of base stations that large gradients will usually intervene, but not so remote as to cause great disparity in other meteorologic conditions. Within the interior districts of the United States these limitations would apply to distances from 100 to 300 miles.

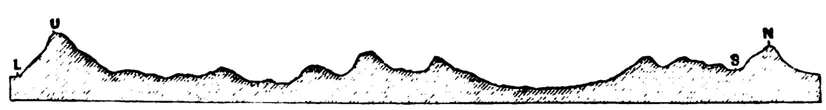


FIG. 31.—Ideal Land-Profile, to illustrate the use of an Outlying Base Station.

The special procedure proposed for such a case is as follows: Establish a base station at S in the midst of the distant group of new stations, and conduct there a series of observations for so long a time as observations are made at new stations in the vicinity. In selecting the site for the outlying base station,—it is better, when feasible, to approximate it in altitude to the new stations, its vertical relation to the main pair of base stations being comparatively unimportant. If its altitude is not otherwise known, it can be computed by reference to the principal base

stations, using either the entire series of synchronous observations or such a selection from them as may be indicated by the variations of wind during the period. In the computation of the new stations, refer each of them to the outlying base station, but employ the measurement of density afforded by the simultaneous observations at the pair of principal base stations.

A modification of the general formula adapts it to the special case:

Let n stand for the barometer reading at a new station of the outlying group. Represent by r the synchronous reading at the outlying base station. Call R the height of the outlying base station (S) above the lower base (L) of the pair, and A′ the height of the new station (N) above the outlying base (S). Give to l, u, B, and D the same significations as before. It is needless to repeat here the various steps by which the special formula is deduced, for the reasoning is identical with that for the derivation of the formula on page 442. We therefore write at once—

$$A' = B\frac{\log r - \log n}{\log l - \log u} + \frac{A'\left[(B-2R)-A'\right]}{D} \quad . \quad . \quad . \quad . \quad (23)$$

In the application of this formula the table published at the end of this paper can be used, with this difference only, that in place of B as an argument the quantity B−2 R must be substituted.

In any application of the more general system for the elimination of gradients, outlined in the preceding section, it will frequently occur that the new station is situated so near to one of the auxiliary stations that the gradient referrible to the intervening distance is inconsiderable. In every such case the formula just given can be employed with economy of labor and without prejudice to precision.

8. SUMMARY.

Our search has not resulted in the discovery of an immediately practicable way of improving the new formula, but it has served to indicate a line of investigation which promises to advance the subject.

If ever a string of thoroughly equipped stations shall be established upon a steep mountain slope and maintained for a sufficient term, it is probable that the discussion of their observations will afford a new and better value for the constant of the new formula; and it is possible that it may so far define the law of the vertical distribution of thermic density that the form of the thermic term of the formula will need to be changed. It may also dictate the introduction of a factor dependent on the season of year, and it may possibly demonstrate the advantage of employing three base stations in the vertical series instead of two.

Such a discussion could not fail to throw light upon the relation of di-

urnal curves of pressure to altitude, and by so doing it might indicate some manner of avoiding the hypsometric errors which have a daily period.

It is believed that in general all corrections for atmospheric gradient should be applied to the barometric data previous to the introduction of the latter into the hypsometric formula; but it has been pointed out that in a certain class of cases gradient errors can be avoided by a modification of the general hypsometric method, with a corresponding modification of the formula. The modified formula (23) is in point of fact of a more general nature than the one proposed for ordinary use (7), for in it the new line is made independent of the vertical base, whereas the latter requires an extremity of the new line to coincide with an extremity of the vertical base.

It has been discovered that wind may attain importance as an unfavorable condition of observation, and the necessity for investigating its influence upon the indication of the barometer has been pointed out. The harmony of a series of altitude determinations upon the flanks of Mount Washington was increased about 40 per cent by the rejection of those based on observations made during the prevalence of winds.

The harmony of the Mount Washington determinations after the elimination of this disturbing factor, is indeed so conspicuous as to suggest that the hypsometric method has in this case almost eradicated the errors incident to abnormal atmospheric inequality,—little remaining besides the errors incident to the making of the observations. To test this matter recourse has been had to the mathematical theory of probabilities, and an attempt has been made to ascertain, first, the probable error of barometric instrumentation and the probable error of a single hypsometric determination at Mount Washington as dependent upon instrumentation; and second, the probable error proper of the same determination as deduced from residuals.

The probable error of barometric instrumentation may be defined to be that deviation from the proper or indicative height of the mercurial column which is most likely to be incurred in making an observation. It includes the errors dependent on the imperfection of the scale of the instrument, on imperfect correction for the capillarity of the tube, on the inaccuracy of the adjustments that have to be made by the observer before the reading, on the inaccuracy of the reading itself, and on the inaccuracy of the determination of the temperature of the instrument. If one has a long series of independent observations or measurements of the same quantity, he is enabled, by the application of a simple mathematical formula, to deduce the probable error of a single measurement. In the use of a single barometer such a series is not obtained, because the quantity measured—the pressure of the atmosphere—is variable, and in a series of observations it is impossible to discriminate between small errors of observation and small changes of atmospheric pressure. But when two barometers are placed side by side and are subjected

to a series of synchronous observations, the differences between the readings taken in pairs constitute a series of measurements from which it is possible to deduce the probable error of instrumentation.

The writer has made six determinations—two from a series of comparative readings made in connection with the Mount Washington observations and published on page 534 of the Report of the Chief Signal Officer for 1873, and four from series contained in the barometric records of the Geological Survey. The series published by the Signal Officer were made by the same observers who occupied the four stations on Mount Washington, and with the same instruments, and would furnish the best possible criterion of the accuracy of that work if they were sufficiently extended. One of them, however, contains only five comparative readings of three barometers, and the other seven comparative readings of three barometers; and these data are too scant to afford a trustworthy estimate of the probable error. The following is a summary of the results:

Series.	Number of Comparisons.	Deduced Probable Error of a Single Reading.
1 (Signal Service)	10	± .0030 inch.
2 (Signal Service)	14	± .0030 inch.
3 (Geological Survey)	56	± .0041 inch.
4 (Geological Survey)	79	± .0032 inch.
5 (Geological Survey)	100	± .0014 inch.
6 (Geological Survey)	100	± .0023 inch.
	Weighted Mean	± .0027 inch.

Each series of comparisons by the Geological Survey was carried through a period of several days, during which time the barometer rose or fell one or more tenths of an inch, so that different parts of the scale and tube were brought into use. The series of observations by the Signal Service observers were each made within an hour's time, and exhibit small barometric ranges. The test in the former case was therefore somewhat more rigorous, and there is no reason for presuming that a longer series of observations by the Signal Service observers would have afforded a smaller probable error of instrumentation. In assigning to each of their readings an error of ±.0027 inch (the general or weighted mean of all the determinations) we seem in no danger of underrating the precision of their work.

In the computation of altitude the errors of observation at the different stations affect the result by different amounts, and these amounts depend upon the relative and absolute altitudes of the stations. We shall not describe these relations, but merely mention that they have been taken into consideration. Taking due account of them, the assumed error of instrumentation at the several stations gives 3.8 feet as the probable error of a single determination of the altitude of Station 2 above Station 4, and 3.4 feet as the probable error of a determination of Station 3.

The individual determinations of altitude constitute a series of measurements of a constant quantity, and yield to the simple application of the mathematical formula the probable error of a single determination. Seventy-four determinations of Station 2, made at hours when the velocity of the wind did not exceed 10 miles per hour at any station, yield 6.8 feet as the probable error of a single determination. Sixty-nine measurements of the height of Station 3, made at hours when the wind upon Station 1 did not exceed 2 miles per hour, give 3.7 feet for the probable error of a single determination.

Combining these results, it appears that the probable error of a determination of Station 2, made by the new hypsometric method under favorable conditions as regards wind, is 6.8 feet, and that 3.8 feet may be assigned to instrumentation. The remaining error, which must be assigned to other causes, is expressed by $\sqrt{(6.8)^2 - (3.8)^2} = \pm 5.6$ feet. The corresponding error of the determination of Station 3 is $\pm$ 3.7 feet, of which $\pm$ 3.4 feet is assignable to instrumentation, and only $\pm$ 1.5 feet to other causes.

It would be hazardous to pin our faith to these figures and affirm that the new hypsometric method has determined the height of a station with such precision that the uneliminated errors due to atmospheric inequality affect the result by less than 2 feet, but it may safely be said that barometric hypsometry has been brought to such a stage that the influence of errors of instrumentation is distinctly appreciable in the result; and there is full warrant for the declaration that observations designed for the future refinement of hypsometric method must themselves be of the highest grade. The employment of inferior or of untested instruments, of observatories badly located, or of unskillful or untrustworthy observers, would suffice to nullify any attempt which might be made to give the science of barometric hypsometry a better experimental basis.

CHAPTER V.

LIMITATIONS TO UTILITY.

The new hypsometric method is not of universal application. It is not indeed subject to local restrictions like the empiric, but there are certain conditions under which its employment is impracticable, and certain others under which it is disadvantageous. The majority of these would occur to the geographer at once, but there are some which might not, and it is proper to enumerate them all for the sake of avoiding any possible misapprehension. There are, moreover, certain conditions which restrict the use of the barometer by whatever method, and for the sake of symmetry these will be included in the list.

A. *The* barometer *will not be employed:*

(1) *When the demand for precision is beyond its competence.* It is admitted by all barometricians that there is a degree of precision attainable by other instruments to which the barometer can never hope to reach. In the nature of things there is a limit to its powers, and although the apparent position of that limit may be modified by refinements in method, it can never be abolished. The present essay is an attempt to crowd it slightly backward, but is so far from removing it altogether that it serves rather to confirm or reassert its permanence. For such engineering works as canals and railroads the barometer can serve no useful purpose except in reconnaissance.

(2) *When its precision can be equaled at less expense.* The better class of modern geographic work is performed by means of observations made at stations which are intervisible, and in proportion as the demands for accuracy increase, and more is attempted in the delineation of details, the interspaces between the stations occupied by the topographer are progressively diminished. The topographer is able to compute the relative height of all points visible to him from any station, provided their distances become known, by measuring the angles of elevation or depression which they subtend; and since other stations of his system are always included among the points of observation, he is able in this manner to carry through his field a connected system of altitude determinations. If the stations are widely separated, such determinations of altitude are of little value by reason of the errors introduced by atmospheric refraction, but if the stations are near together, the determinations may have a high degree of precision. When, therefore, in the progress of geographic refinement the stations of the topographer approach so near to each other that the precision of the measurement of

altitudes by angulation becomes equal to the precision obtainable by means of the barometer, barometric hypsometry receives at once a formidable competitor. Indeed it encounters an invincible antagonist, for the expense of reading vertical angles, when it is performed as a mere accessory to the general work of the topographer, is notably less than the expense of transporting and observing barometers,—to say nothing of the expense of maintaining base stations. The most thorough geographic work will therefore dispense altogether with the barometer.

B. *The* new method *will not be used:*

(3) *When sites for the necessary base stations are not available.* The method demands that its two base stations shall be upon a steep slope, and that their difference in altitude shall not be unduly small. The first demand is dictated by the importance of avoiding gradient errors; the second by two independent considerations. In the first place, the air column whose weight and density are determined by the observations at these stations, is necessarily composed in part of the layer adjacent to the earth's surface, which is abnormally affected by the sun's heat and undergoes rapid changes, and in part of the upper and more general portion of the atmosphere, which changes more slowly. It is the density of the latter which it is important to know, and the greater the height of the column weighed the smaller is the influence of its abnormal superficial factor. Theoretically, a very short column would give no better indication of the density factor of the atmosphere than do the measurements of temperature and humidity heretofore customarily depended on. The second consideration arises from the unavoidable errors of observation. These depend upon the instruments and the observers, and are independent of the height of the air column. They consequently affect the measurement of the density of a short column in greater ratio than that of a tall column.

No definite limit can be assigned to the admissible interval between the base stations, because it must vary with circumstances. If the new stations are all in the immediate vicinity of the base stations, and fall between them in point of altitude, the requirements are not so great as when the new stations are widely scattered. It may be said without qualification, however, that a region in which the slopes are all gentle is unsuited to the employment of the new method, and can be best served by the "ordinary" method.

(4) *When the demand for precision is not beyond the capacity of a cheaper method.* The class of cases debarred by this limitation is large, for it includes every reconnaissance made as a preliminary to more exact work,—whether of a general geographic nature or for some such special purpose as the construction of a railroad.

(5) *When the unavoidable errors from gradient are great.* Non-periodic or cyclonic gradient is a function of horizontal distance. It depends, of course, upon many other things, but the *probable* hypsometric error arising from this source is always relatively great when the distance

between base and new stations is great, while it is comparatively unaffected by the vertical relations of base and new stations. The new hypsometric method and the "ordinary" compete only in the elimination of errors arising from inaccurate determinations of density, while they alike fail to remove gradient errors. When the new stations are near the base, gradient errors are inconsiderable, and the superior ability of the new method to contend with density errors renders its employment advantageous; but when the new stations are remote from the base, gradient errors become so large as to overwhelm those arising from imperfect determination of density, and then the accomplishment of the two methods is practically the same. If, therefore, all the new stations are remote from the locality selected for a base, no commensurate advantage can follow the employment of the more expensive method.

This consideration is enforced by the fact that errors arising from different sources are combined in the general result by means of their squares, and not by simple addition. Suppose, for example, that the computation of the altitude of a new station close to the bases has a probable error (depending on the vertical distribution of densities) of ± 15 feet when the ordinary method is employed, and of ± 10 feet by the new method. Suppose, further, that another new station is at such a distance that its computed altitude has a probable error due to gradient alone of ± 25 feet. Its total probable error by the ordinary method will then be $(\sqrt{(15)^2 + (25)^2} =) \pm 29$ feet, while its total error by the new method will be $(\sqrt{(10)^2 + (25)^2} =) \pm 27$ feet. The saving effected by the substitution of the new method for the old is 33 per cent in the case of the nearer new station, and only 7 per cent in the case of the more remote.

Here again no absolute rule can be laid down, for when the new stations differ greatly in altitude from that base to which they would be referred by either method (or, more simply, when the new lines are high), density errors are correspondingly great, and a comparatively large gradient error can be introduced without depriving the new method of its advantage.

(6) *When the new stations are few.* This limitation is connected purely with expense, and is not of universal application. It is perhaps rather an amplification of the fourth limitation. As a rule, the more elaborate and refined hypsometric methods can be economically employed only in surveys where many points are to be determined, so that the expense of equipping and maintaining base stations may be shared by a large number of new stations.

(7) *When the new station falls far without the vertical base.* The numerous comparative computations which have been made for testing the value of the new method have served to show that while it gives better determinations of points intermediate in height between the upper and lower bases, and of points a short distance above the upper base or below the lower, it nevertheless gives poorer determinations of points far

above the upper base or far below the lower. An attempt has been made, by discussing the available figures, to ascertain the limit at which the advantage of the new method ceases, but the results have not been accordant. It may be said in a general way, however, that when the vertical space separating the new station from the nearer base station is not more than one-half the vertical base line, the new method gives the better results, and that when the space separating the new station from the nearer base station is greater than the vertical base line, the better results are given by the "ordinary" method.

It follows from this, first, that when circumstances will permit, the upper and lower base stations should be so chosen as to include in their vertical interspace all or nearly all the proposed new stations. It follows, second, that when it is impracticable so to dispose the base stations that the new stations fall within the range of utility of the new method, there is no advantage in using more than one base station. It follows, third, that when two base stations have been used in field-work it will nevertheless be advisable in the case of some new stations to ignore the observations at the more remote base and perform the computation by the "ordinary" method.

It may appear to the reader that a system hemmed in by so many restrictions is practically useless; but the field remaining to the new method is in reality a broad one, including, unless the merits of the method are here overrated, the major part of the barometric hypsometry of the United States for the next decade. The reform was suggested by the needs of the geographic surveys conducted by the government during the past fifteen years in the mountainous region lying between the Great Plains and the Pacific Ocean, and it is especially adapted for use in such a region. The preliminary reconnaissances, which did not require the degree of precision it affords, have now been made, but the time has not yet arrived for that more elaborate geographic work which will dispense with the barometer altogether and employ only the theodolite and kindred instruments for the determination of its vertical element. For the present the barometer holds its place as the chief hypsometric instrument, and the principal work to which it is an accessory demands that it shall be so handled as to afford the highest practicable degree of precision.

CHAPTER VI.

THE WORK OF OTHERS.

In the preceding pages no attempt has been made to credit the founders and the numerous promoters of the science of barometric hypsometry with the ideas and principles derived from them. The citation of authorities has even been avoided, so far as possible, because the mention of a few among so many might seem to make an invidious distinction, while giving due credit to all would involve the full presentation of the history of the subject—a work for which the writer has neither time nor inclination. The reader who desires to know the successive steps by which the barometer has been brought to its present measure of utility can find his wishes fully met by consulting the works of Rühlmann, Whitney, Schreiber, and Cross.*

It is impossible, however, to pass without mention the work of those who have to some extent anticipated the hypsometric method forming the subject of this paper.

One of the leading and essential propositions of the paper is—to determine the condition of the atmosphere at the moment when a measurement of height is made, by means of the synchronous barometric measurement of a known height. This was first advanced by the writer at a meeting of the Philosophical Society of Washington, in May, 1877, at which time he supposed it to be novel. He has since learned that he was antedated in publication by no less than two hypsometers, while it is probable that a third also anticipated him in the conception of the idea. Nevertheless, the announcement of his method was not devoid of novelty, for he differed radically from his predecessors in his manner of developing and applying the idea.

The earliest investigator who has recorded his use of the principle is Plantamour. In his hypsometric method, a description of which has already been given, he recomputed the height of St. Bernard above Geneva at the instant of each observation upon which a computation of the height of a new station was based, and by comparing this computed height of St. Bernard with the known real height he obtained a

* Rühlmann's "Barometrischen Hohenmessungen," Leipsic, 1870.
Whitney's "Contributions to Barometric Hypsometry, 1874; Chapters I and III."
Schreiber's "Handbuch der barometrischen Hohenmessungen," Weimar, 1877; Chapter VIII.
Appalachia, vol. II, p. 201, May, 1881; Address on the "Barometric Measurement of Heights," by Charles R. Cross.

criterion for judging of the momentary condition of the atmosphere. His two base stations were so far apart that it was impossible to discriminate the effect of a false estimate of atmospheric density from the effect of gradient, and in his computations he assumed that his determination of density (that is, of temperature and humidity) was correct, and regarded the error of his computed height of St. Bernard as an indication of the effect of gradient alone. So regarding it, he proposed no plan for eliminating it, but simply used it as a means of giving weight to the synchronous determination of the required altitude as compared with other determinations of the same. It may seriously be doubted whether his assumption was warranted; but be that as it may, there can be no question that his weighting of individual determinations had a beneficial effect upon his ultimate result.

His method differs primarily from the one here advanced in that it used the redetermination of a known height to measure gradient only, while it is here used to measure density only. Density is by his method determined solely by means of thermometric and psychrometric observations, made simultaneously with those of the barometers and corrected by the aid of the mean errors of long series of observations.

A method of hypsometry proposed by Lieutenant William L. Marshall was first given to the world in 1877,* but appears to have been practiced by him for some years prior to that time. In the main it is the system of Williamson, but it includes a number of valuable innovations, the chief of which is the following:

Within the field of survey are established a pair of base stations, one high and the other low, but not widely separated horizontally. Their difference in altitude is either determined by some independent method or else from the means of the observations for the entire season. For each week of hypsometric work a special computation of their difference in altitude is made, in which the weekly means of the barometric, thermometric, and psychrometric observations at the two stations are employed. The standard difference in height is then divided by this computed difference, and the quotient is regarded as a correction factor. All barometric differences of altitude determined during the week in localities where the diurnal changes of temperature and other climatic characteristics are similar to those at the upper base station, are then multiplied by this factor, after having been computed from the observations of pressure, temperature, and humidity in the way prescribed by Williamson.

This system agrees with the one here advanced in using the rede-

* "United States Geological Surveys West of the 100th Meridian, in charge of First Lieut. George M. Wheeler, Vol. II. Astronomy and Barometric Hypsometry, Part II. Results in Barometric Hypsometry obtained during the years 1871, 1872, 1873, 1874, and 1875, reported by First Lieut. William L. Marshall, Corps of Engineers, U. S. A. Washington, Government Printing Office, 1877." The novel element of his hypsometric system is described on pages 522 and 523 of the volume.

termination of a known height as a means of measuring the density of the atmosphere at a given moment. Its chief difference consists in the fact that instead of ignoring altogether the observations of temperature and moisture, it first introduces them into the computations, and then endeavors to counteract their vicious effect by a process of cancellation. The untrustworthiness of the thermometric and psychrometric determinations as indices of the density of the air column used in hypsometry is clearly pointed out by Lieutenant Marshall, and his weekly corrective factor was devised for the purpose of eliminating the errors to which they give rise. But he nevertheless admitted them into his computations, both of the altitude of the new station and of the height of the vertical base, and only sought to neutralize their ill effect in one case by balancing against it their ill effect in the other. Having once admitted them, there was perhaps no better mode of neutralizing the errors they caused; and it is probable that his device materially enhanced the accuracy of his hypsometric work.

It is a possible defect of his system that it takes no account of the fact pointed out by Plantamour and Whitney that the correction necessary at high altitudes is not the same as that required at low altitudes. So long as his correction factors are applied to the computed differences in level of base and new stations whose altitudes approximate respectively those of the upper and lower limits of his vertical base line, a good result is to be expected; but it is to be doubted whether the application can be extended to points differing greatly in height from the two stations limiting the vertical base.

In 1870, Dr. Richard Rühlmann, of Carlsruhe, published an elaborate memoir in which he reviewed the entire subject of barometric hypsometry. After describing the formulas and methods of others, he developed a formula and method of his own. His formula is a modification of that of Laplace, and represents the difference in level of two stations as a function of the observed atmospheric pressures, temperatures, and moistures at the two stations and of the latitudes of the stations. He differs from his predecessors chiefly in his manner of determining the atmospheric temperature. For this purpose he makes use of two stations whose difference in level is known, and from the observed pressures and moisture factors at these stations he computes the temperature of the intervening air column. The temperature thus derived he afterwards applies (by a special method to be described presently) in the computation of the unknown difference in level of two other stations. He thus agrees with the writer in rejecting the indications of the thermometer as a measure of atmospheric temperature, but differs from him in that he retains the observations of the psychrometer. With this exception he employs the same principle, for while the new method deduces the density of an air column of known height from a measurement of its weight, Rühlmann deduces the tem-

perature of such a column from measurements of its weight and humidity. The new method then proceeds to apply the deduced density, in connection with observed pressure, to the computation of an altitude, and Rühlmann similarly proceeds to apply the deduced temperature, in connection with observations of pressure and humidity, to the computation of an altitude. The errors arising from false estimates of temperature so far outweigh those from false estimates of moisture that the practical difference between the two systems cannot be great, although theoretically the considerations leading to the rejection of the temperature observations apply with even greater force to the less veracious observations of humidity.

But while Rühlmann's method has thus, in principle, substantially anticipated the one here developed, it is applied by him in a very different manner. He gives no consideration whatever to single observations nor to a single pair of base stations, but says that a district of country in which his barometric method is to be applied must be furnished in advance with a large number of meteorologic base stations of which the latitudes, longitudes, and altitudes are known, and at which long series of observations have been made. The new stations must be occupied for the same period—a period so long that all minor inequalities incident to atmospheric changes will be eliminated by cancellation. With these elaborate data in hand, and making use only of the mean values, for each station, of the pressure and humidity, he proceeds as follows: First, he arranges the base stations in pairs, combining each one with every other one which differs from it considerably in altitude, and for each pair he computes, by the aid of their known heights and latitudes, and of the observed pressures and humidities, the mean temperature of the intervening air column. This temperature he ascribes to that point which is intermediate between the two stations both in distance and height. This series of computations gives him an estimate of the temperature of a large number of points in space, the positions of which are indicated by their latitudes, longitudes, and altitudes. He then assumes that the temperature of any point whatever in the district is equal to a certain factor, plus a second factor multiplied by the latitude of the point, plus a third factor multiplied by its longitude, plus a fourth factor multiplied by its altitude; and proceeds, by the aid of the individual temperatures already computed and by means of the method of least squares, to compute the values of these factors. Having computed them, he is furnished with a temperature formula by means of which he can compute the mean temperature of any point within the district. Taking now a pair of stations of which he wishes to determine the difference in altitude, he deduces from their known latitudes, their known longitudes, the known altitude of one, and the approximate altitude of the other, the latitude and longitude and approximate altitude of the point midway between them; and thus obtains, through the temperature formula, the mean temperature of the intervening air column.

This mean temperature enters his hypsometric formula in place of the mean of the thermometric readings, and the difference in altitude is then computed. If it differs notably from the approximate value given directly by the readings of the barometers, a second and more refined determination of the temperature is made, and the computation is repeated.

So far as the writer is aware, this cumbrous method has never been put in practice. It is quite inapplicable to general geographic work because it demands long series of observations, and if it has a field of utility it probably lies in the determination of the altitudes of meteorologic stations where observations are continuously made as a means of predicting the weather.

It thus appears that the precise ground covered by the new method has not before been occupied. Plantamour recomputed a known height for the purpose of ascertaining the temporary gradient. Marshall did the same thing for the purpose of ascertaining the temporary hypsometric error. Rühlmann did the same for the purpose of determining the local mean temperature. The writer only has performed the computation for the purpose of ascertaining the local and temporary mean density of the air column. Plantamour computed the altitude of his new station from the observed pressures, temperatures, and humidities (applying also empirical corrections), and used his coincident determination of a known height only as a criterion for judging whether the temporary meteorologic conditions were favorable. Marshall also computed the height of the new station by means of the observed pressures, temperatures, and humidities, and used his recomputation of a known height as a means of expunging the errors he had introduced. Rühlmann proposes to compute the height of the new station by means of the observed pressures and humidities, but substitutes for the observed temperatures a value derived from the recomputation of known heights. The present method only has altogether rejected observations of temperature and humidity and computed the height of the new station by the sole means of observed pressures.

Acknowledgments.—In the conduct of my investigation I have been greatly indebted to the courtesy and assistance of others. Professor J. D. Whitney and Colonel R. S. Williamson have afforded me the use of unpublished barometric records. General W. B. Hazen, Chief Signal Officer of the Army, has favored me with important data from the archives of the Weather Bureau, and the library of his office has been of the utmost service to me. I am indebted to my friends Professor Cleveland Abbe, Mr. M. H. Doolittle, Mr. Marcus Baker and Mr. H. A. Hazen for much kind counsel and assistance. The computations pertaining to the work, which were exceedingly onerous, have been performed at the expense of the Geological Survey by Mr. P. C. Warman, Mr. Paul Holman, and Mr. Albert L. Webster.

CHAPTER VII.

ON THE USE OF THE TABLE.

The barometric formula developed in Chapter II (Equation 17) is—

$$A = B\frac{\log l - \log n}{\log l - \log u} + \frac{A(B-A)}{490000}$$

in which

l is the atmospheric pressure (or the reading of the barometer) at the lower base station;

u is the pressure at the upper base station;

n is the pressure at the new station;

A is the height, in English feet, of the new station above the lower base station; and

B is the height, in feet, of the upper base station above the lower, or, in other words, is the height of the vertical base line.

The first term of the formula is otherwise designated by a,—

$$a = B\frac{\log l - \log n}{\log l - \log u}$$

and is called the *logarithmic term*, or *approximate difference in altitude;* the second, $\frac{A(B-A)}{490000}$, is called the *thermic term*.

B, l, u, and n are known quantities, and from them a is computed by the aid of logarithms. (See page 449.) The thermic term is obtained from the table (pages 556–561), with B and a as arguments.

In each page of the table the left-hand column contains the values of a, and the horizontal lines at the top and bottom margins give the values of B. The pages are arranged in pairs; the left hand of each pair includes the values of B from 1,000 to 5,000, and the right from 6,000 to 10,000. Each page has nine interpolation columns at the right, containing increments for the numbers in the columns at the left, to be used when B is not expressed in even thousands of feet.

The first pair of pages serve when a is negative, the second and third pairs when a is positive.

In the use of the table there arise three cases, which are illustrated by the following three examples. In the first the new station is intermediate between the two bases; in the second it is higher than the upper base; in the third it is lower than the lower base.

FIRST EXAMPLE.

(New Station Intermediate.)

What is the value of the thermic term when $B = 4{,}000$ and $a = 1{,}200$?

From the intersection of the line which contains $+1{,}200$ as a value of a and the column headed 4,000, we obtain $+6.9$, which is the required value of the thermic term.

SECOND EXAMPLE.

(New Station Above Upper Base Station.)

What is the value of the thermic term when $B=3{,}600$ and $a=5{,}727$?

Let us consider B as composed of 3,000 and 600, and a as composed of 5,700 and 27.

From the intersection of the line containing $+5{,}700$ as a value of a and the column headed 3,000 we obtain the correction . . . -30.9

To allow for the 600 we take from the intersection of the same line with the interpolation column headed 6 . . . . . $+\ 6.8$

To allow for the 27 we take from the column headed 3,000 the corrections corresponding to $a=5{,}700$ and $a=5{,}800$, subtract one from the other, divide the remainder by 100, and multiply the quotient by 27, thus:

$$\frac{30.9 - 32.6}{100} \times 27 = \quad . \ . \ . \ . \ . \ . \ . \ . \quad -\ 0.5$$

Adding, we obtain the total correction, or the value of the thermic term . . . . -24.6

THIRD EXAMPLE.

(New Station Below Lower Base Station.)

What is the value of the thermic term when $B=7{,}864$ and $a= -2{,}400$?

Consider B as composed of 7,000, 800, 60, and 4.

With $B = 7{,}000$ and $a = -2{,}400$, we obtain . . . . -47.2

With 800, we obtain from the interpolation column . . . . . $-\ 4.1$

The interpolation element for 60 (one-tenth of that for 600) is . $-\ \ .3$

The element for 4 is too small to note.

The required value is the sum of these numbers . . . . . -51.6

SIGNS.

The formula and the table assume the origin of distances to be at the lower base station. The vertical distances of all higher points are

affected by the plus sign, of lower points by the minus sign. The vertical base, B, is positive. A is positive when the new station is above the lower base station; negative when it is below. The value of the thermic term is positive when the new station is intermediate between the bases; negative when it is not intermediate. It is numerically additive to *a* when the new station is lower than the upper base station; subtractive when the new station is higher.

The interpolation elements are given the plus sign when the series of numbers to which they pertain is algebraically ascending; they are given the minus sign when it is descending. Thus, in the second example, 6.8 is made positive because the horizontal series in the table ascends from −30.9 to −19.5; while 0.5 is made negative because the vertical series descends from −30.9 to −32.6.

The computer who has to determine a large number of new stations by reference to a single pair of base stations can simplify his work by constructing a special table adapted to his particular value of B,—unless that value is measured by even thousands of feet. The special table will contain but two columns; one for values of *a*, and one for the corresponding values of the thermic correction. The latter can be simply derived, by the aid of the interpolation columns, from one of the columns of the printed table. The special table need not extend beyond the range of actual values for *a*, and ordinarily will be very short. In using it the value of *a* will be the only argument.

TABLE OF VALUES OF THERMIC TERM, $\frac{A\,(B-A)}{D}$, IN FEET.

a=Approximate Altitude, in Feet.	B=Vertical Base, in Feet.					Additional Hundreds of Feet.								
	1,000	2,000	3,000	4,000	5,000	1	2	3	4	5	6	7	8	9
− 5,000	−62.6	−73.2	−83.9	−94.6	−105.3	1.1	2.1	3.2	4.3	5.3	6.4	7.5	8.6	9.6
4,900	60.3	70.7	81.1	91.6	102.1	1.0	2.1	3.1	4.2	5.2	6.2	7.3	8.3	9.4
4,800	58.1	68.2	78.4	88.7	98.9	1.0	2.0	3.1	4.1	5.1	6.1	7.1	8.2	9.2
4,700	55.9	65.8	75.8	85.8	95.8	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0
4,600	53.7	63.4	73.2	83.0	92.8	1.0	2.0	2.9	3.9	4.9	5.9	6.9	7.8	8.8
− 4,500	−51.6	−61.1	−70.6	−80.2	−89.8	1.0	1.9	2.9	3.8	4.8	5.7	6.7	7.6	8.6
4,400	49.5	58.8	68.1	77.5	86.9	0.9	1.9	2.8	3.7	4.7	5.6	6.5	7.5	8.4
4,300	47.5	56.5	65.6	74.8	84.0	0.9	1.8	2.7	3.6	4.6	5.5	6.4	7.3	8.2
4,200	45.5	54.3	63.2	72.1	81.1	0.9	1.8	2.7	3.6	4.5	5.3	6.2	7.1	8.0
4,100	43.5	52.1	60.8	69.5	78.3	0.9	1.7	2.6	3.5	4.4	5.2	6.1	7.0	7.8
− 4,000	−41.6	−50.0	−58.4	−66.9	−75.5	0.8	1.7	2.5	3.4	4.2	5.1	5.9	6.8	7.6
3,900	39.7	47.9	56.1	64.4	72.7	0.8	1.7	2.5	3.3	4.1	5.0	5.8	6.6	7.4
3,800	37.9	45.9	53.9	61.9	70.0	0.8	1.6	2.4	3.2	4.0	4.8	5.6	6.4	7.2
3,700	36.1	43.9	51.7	59.5	67.4	0.8	1.6	2.3	3.1	3.9	4.7	5.5	6.3	7.0
3,600	34.4	41.9	49.5	57.1	64.8	0.8	1.5	2.3	3.0	3.8	4.6	5.3	6.1	6.8
− 3,500	−32.7	−40.0	−47.4	−54.8	−62.2	0.7	1.5	2.2	2.9	3.7	4.4	5.2	5.9	6.6
3,400	31.0	38.2	45.3	52.5	59.7	0.7	1.4	2.2	2.9	3.6	4.3	5.0	5.7	6.5
3,300	29.4	36.3	43.3	50.2	57.3	0.7	1.4	2.1	2.8	3.5	4.2	4.9	5.6	6.3
3,200	27.8	34.6	41.2	48.0	54.8	0.7	1.3	2.0	2.7	3.4	4.1	4.7	5.4	6.1
3,100	26.3	32.8	39.3	45.9	52.4	0.7	1.3	2.0	2.6	3.3	3.9	4.6	5.2	5.9
− 3,000	−24.8	−31.1	−37.4	−43.8	−50.1	0.6	1.3	1.9	2.5	3.2	3.8	4.4	5.1	5.7
2,900	23.4	29.5	35.5	41.7	47.8	0.6	1.2	1.8	2.4	3.1	3.7	4.3	4.9	5.6
2,800	22.0	27.8	33.7	39.6	45.5	0.6	1.2	1.8	2.3	2.9	3.5	4.1	4.7	5.3
2,700	20.6	26.3	31.9	37.6	43.3	0.6	1.1	1.7	2.3	2.8	3.4	4.0	4.5	5.1
2,600	19.3	24.8	30.2	35.7	41.2	0.5	1.1	1.6	2.2	2.7	3.3	3.8	4.4	4.9
− 2,500	−18.1	−23.3	−28.5	−33.8	−39.1	0.5	1.1	1.6	2.1	2.6	3.2	3.7	4.2	4.7
2,400	16.9	21.8	26.8	31.9	37.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5
2,300	15.7	20.5	25.2	30.1	34.9	0.5	1.0	1.4	1.9	2.4	2.9	3.4	3.8	4.3
2,200	14.5	19.1	23.7	28.3	32.9	0.5	0.9	1.4	1.8	2.3	2.8	3.2	3.7	4.1
2,100	13.4	17.8	22.2	26.6	31.0	0.4	0.9	1.3	1.8	2.2	2.6	3.1	3.5	4.0
− 2,000	−12.4	−16.5	−20.7	−24.9	−29.1	0.4	0.8	1.3	1.7	2.1	2.5	2.9	3.3	3.8
1,900	11.3	15.3	19.3	23.2	27.2	0.4	0.8	1.2	1.6	2.0	2.4	2.8	3.2	3.6
1,800	10.4	14.1	17.9	21.6	25.4	0.4	0.8	1.1	1.5	1.9	2.3	2.6	3.0	3.4
1,700	9.4	13.0	16.5	20.1	23.6	0.4	0.7	1.1	1.4	1.8	2.1	2.5	2.8	3.2
1,600	8.5	11.9	15.2	18.6	21.9	0.3	0.7	1.0	1.3	1.7	2.0	2.3	2.7	3.0
− 1,500	− 7.7	−10.8	−13.9	−17.1	−20.2	0.3	0.6	0.9	1.2	1.6	1.9	2.2	2.5	2.8
1,400	6.9	9.8	12.7	15.6	18.6	0.3	0.6	0.9	1.2	1.5	1.8	2.0	2.3	2.6
1,300	6.1	8.8	11.5	14.2	17.0	0.3	0.5	0.8	1.1	1.4	1.6	1.9	2.2	2.4
1,200	5.4	7.9	10.4	12.9	15.4	0.3	0.5	0.8	1.0	1.3	1.5	1.8	2.0	2.2
1,100	4.7	7.0	9.3	11.6	13.9	0.2	0.5	0.7	0.9	1.2	1.4	1.6	1.8	2.1
− 1,000	− 4.1	− 6.2	− 8.2	−10.3	−12.4	0.2	0.4	0.6	0.8	1.0	1.2	1.5	1.7	1.9
900	3.5	5.4	7.2	9.1	11.0	0.2	0.4	0.6	0.8	0.9	1.1	1.3	1.5	1.7
800	2.9	4.6	6.2	7.9	9.6	0.2	0.3	0.5	0.7	0.8	1.0	1.2	1.3	1.5
700	2.4	3.9	5.3	6.8	8.2	0.1	0.3	0.4	0.6	0.7	0.9	1.0	1.2	1.3
600	1.9	3.2	4.4	5.7	6.9	0.1	0.3	0.4	0.5	0.6	0.8	0.9	1.0	1.1
− 500	− 1.5	− 2.6	− 3.6	− 4.6	− 5.7	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
400	1.1	2.0	2.8	3.6	4.5	0.1	0.2	0.3	0.3	0.4	0.5	0.6	0.7	0.8
300	0.8	1.4	2.0	2.7	3.3	0.1	0.1	0.2	0.3	0.3	0.4	0.4	0.5	0.6
200	0.5	0.9	1.3	1.7	2.1	0.0	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.4
100	0.2	0.4	0.6	0.8	1.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
	1,000	2,000	3,000	4,000	5,000	1	2	3	4	5	6	7	8	9

TABLE OF VALUES OF THERMIC TERM, $\frac{A\ (B-A)}{D}$, IN FEET.

a=Approximate Altitude, in Feet.	B=Vertical Base, in Feet.					Additional Hundreds of Feet.								
	6,000	7,000	8,000	9,000	10,000	1	2	3	4	5	6	7	8	9
− 5,000	−116.1	−126.9	−137.7	−148.6	−159.6	1.1	2.2	3.3	4.3	5.4	6.5	7.6	8.7	9.8
4,900	112.7	123.3	133.9	144.6	155.3	1.1	2.1	3.2	4.3	5.3	6.4	7.5	8.5	9.6
4,800	109.3	119.7	130.1	140.5	151.1	1.0	2.1	3.1	4.2	5.2	6.3	7.3	8.4	9.4
4,700	106.0	116.1	126.3	136.5	146.8	1.0	2.0	3.1	4.1	5.1	6.1	7.1	8.2	9.2
4,600	102.7	112.6	122.6	132.6	142.7	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0
− 4,500	− 99.5	−109.2	−119.0	−128.7	−138.6	1.0	1.9	2.9	3.9	4.9	5.9	6.8	7.8	8.8
4,400	96.3	105.8	115.3	124.9	134.5	1.0	1.9	2.9	3.8	4.8	5.7	6.7	7.6	8.6
4,300	93.2	102.4	111.8	121.1	130.5	0.9	1.9	2.8	3.7	4.7	5.6	6.5	7.5	8.4
4,200	90.1	89.1	108.2	117.8	126.5	0.9	1.8	2.7	3.6	4.5	5.5	6.4	7.3	8.2
4,100	87.1	95.9	104.7	113.6	122.5	0.9	1.8	2.7	3.5	4.4	5.3	6.2	7.1	8.0
− 4,000	− 84.1	− 92.7	−101.3	−109.9	−118.7	0.9	1.7	2.6	3.5	4.3	5.2	6.1	6.9	7.8
3,900	81.1	89.5	97.9	106.3	114.8	0.8	1.7	2.5	3.4	4.2	5.1	5.9	6.7	7.6
3,800	78.2	86.3	94.5	102.8	111.0	0.8	1.6	2.5	3.3	4.1	4.9	5.7	6.6	7.4
3,700	75.3	83.2	91.2	99.2	107.3	0.8	1.6	2.4	3.2	4.0	4.8	5.6	6.4	7.2
3,600	72.5	80.2	88.0	95.7	103.6	0.8	1.6	2.3	3.1	3.9	4.7	5.4	6.2	7.0
− 3,500	− 69.7	− 77.2	− 84.7	− 92.3	− 99.9	0.8	1.5	2.3	3.0	3.8	4.5	5.3	6.0	6.8
3,400	67.0	74.3	81.6	88.9	96.3	0.7	1.5	2.2	2.9	3.7	4.4	5.1	5.9	6.6
3,300	64.3	71.4	78.4	85.6	92.7	0.7	1.4	2.1	2.8	3.5	4.3	5.0	5.7	6.4
3,200	61.6	68.5	75.4	82.3	89.2	0.7	1.4	2.1	2.8	3.4	4.1	4.8	5.5	6.2
3,100	59.0	65.7	72.3	79.0	85.7	0.7	1.3	2.0	2.7	3.3	4.0	4.7	5.3	6.0
− 3,000	− 56.5	− 62.9	− 69.3	− 75.8	− 82.3	0.6	1.3	1.9	2.6	3.2	3.9	4.5	5.2	5.8
2,900	54.0	60.1	66.4	72.6	78.9	0.6	1.2	1.9	2.5	3.1	3.7	4.4	5.0	5.6
2,800	51.5	57.4	63.5	69.5	75.6	0.6	1.2	1.8	2.4	3.0	3.6	4.2	4.8	5.4
2,700	49.1	54.8	60.6	66.4	72.3	0.6	1.2	1.7	2.3	2.9	3.5	4.1	4.6	5.2
2,600	46.7	52.2	57.8	63.4	69.0	0.6	1.1	1.7	2.2	2.8	3.3	3.9	4.5	5.0
− 2,500	− 44.4	− 49.7	− 55.0	− 60.4	− 65.8	0.5	1.1	1.6	2.1	2.7	3.2	3.7	4.3	4.8
2,400	42.1	47.2	52.3	57.4	62.6	0.5	1.0	1.5	2.0	2.6	3.1	3.6	4.1	4.6
2,300	39.8	44.7	49.6	54.5	59.5	0.5	1.0	1.5	2.0	2.5	3.0	3.4	3.9	4.4
2,200	37.6	42.3	47.0	51.7	56.4	0.5	0.9	1.4	1.9	2.3	2.8	3.3	3.8	4.2
2,100	35.4	39.9	44.4	48.9	53.4	0.5	0.9	1.4	1.8	2.2	2.7	3.2	3.6	4.0
− 2,000	− 33.3	− 37.6	− 41.8	− 46.1	− 50.4	0.4	0.9	1.3	1.7	2.1	2.6	3.0	3.4	3.8
1,900	31.2	35.3	39.3	43.4	47.5	0.4	0.8	1.2	1.6	2.0	2.4	2.9	3.3	3.7
1,800	29.2	33.0	36.9	40.7	44.6	0.4	0.8	1.2	1.5	1.9	2.3	2.7	3.1	3.5
1,700	27.2	30.8	34.4	38.1	41.8	0.4	0.7	1.1	1.5	1.8	2.2	2.6	2.9	3.3
1,600	25.3	28.7	32.1	35.5	38.9	0.3	0.7	1.0	1.4	1.7	2.0	2.4	2.7	3.1
− 1,500	23.4	− 26.6	− 29.7	− 32.9	− 36.2	0.3	0.6	1.0	1.3	1.6	1.9	2.2	2.6	2.9
1,400	21.5	24.5	27.5	30.4	33.4	0.3	0.6	0.9	1.2	1.5	1.8	2.1	2.4	2.7
1,300	19.7	22.5	25.2	28.0	30.8	0.3	0.6	0.8	1.1	1.4	1.7	1.9	2.2	2.5
1,200	17.9	20.5	23.0	25.6	28.1	0.3	0.5	0.8	1.0	1.3	1.5	1.8	2.0	2.3
1,100	16.2	18.5	20.9	23.2	25.6	0.2	0.5	0.7	0.9	1.2	1.4	1.6	1.9	2.1
− 1,000	− 14.5	− 16.6	− 18.7	− 20.9	− 23.0	0.2	0.4	0.6	0.8	1.1	1.3	1.5	1.7	1.9
900	12.9	14.8	16.7	18.6	20.5	0.2	0.4	0.6	0.8	0.9	1.1	1.3	1.5	1.7
800	11.3	13.0	14.7	16.3	18.0	0.2	0.3	0.5	0.7	0.8	1.0	1.2	1.3	1.5
700	9.7	11.2	12.7	14.1	15.6	0.1	0.3	0.4	0.6	0.7	0.9	1.0	1.2	1.3
600	8.2	9.5	10.7	12.0	13.3	0.1	0.3	0.4	0.5	0.6	0.8	0.9	1.0	1.1
− 500	− 6.7	− 7.8	− 8.8	− 9.9	− 11.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
400	5.3	6.1	7.0	7.8	8.7	0.1	0.2	0.3	0.3	0.4	0.5	0.6	0.7	0.8
300	3.9	4.5	5.2	5.8	6.4	0.1	0.1	0.2	0.3	0.3	0.4	0.4	0.5	0.6
200	2.6	3.0	3.4	3.8	4.3	0.0	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.4
100	1.3	1.5	1.7	1.9	2.1	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
	6,000	7,000	8,000	9,000	10,000	1	2	3	4	5	6	7	8	9

TABLE OF VALUES OF THERMIC TERM, $\frac{A\,(B-A)}{D}$, IN FEET.

a = Approximate Altitude, in Feet.	B = Vertical Base, in Feet.					Additional Hundreds of Feet.								
	1,000	2,000	3,000	4,000	5,000	1	2	3	4	5	6	7	8	9
+ 100	+ 0.2	+ 0.4	+ 0.6	+ 0.8	+ 1.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
200	0.3	0.7	1.1	1.6	2.0	0.0	0.1	0.1	0.2	0.2	0.3	0.3	0.3	0.4
300	0.4	1.0	1.6	2.3	2.9	0.1	0.1	0.2	0.2	0.3	0.4	0.4	0.5	0.6
400	0.5	1.3	2.1	3.0	3.8	0.1	0.2	0.2	0.3	0.4	0.5	0.6	0.7	0.7
500	0.5	1.5	2.5	3.6	4.6	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
+ 600	+ 0.5	+ 1.7	+ 2.9	+ 4.2	+ 5.4	0.1	0.2	0.4	0.5	0.6	0.7	0.9	1.0	1.1
700	0.4	1.9	3.3	4.7	6.2	0.1	0.3	0.4	0.6	0.7	0.9	1.0	1.2	1.3
800	0.3	2.0	3.6	5.2	6.9	0.2	0.3	0.5	0.7	0.8	1.0	1.2	1.3	1.5
900	0.2	2.0	3.9	5.7	7.6	0.2	0.4	0.6	0.7	0.9	1.1	1.3	1.5	1.7
1,000	0.0	2.0	4.1	6.2	8.2	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8
+ 1,100	− 0.2	+ 2.0	+ 4.3	+ 6.5	+ 8.8	0.2	0.4	0.7	0.9	1.1	1.3	1.6	1.8	2.0
1,200	0.4	1.9	4.4	6.9	9.4	0.2	0.5	0.7	1.0	1.2	1.5	1.7	2.0	2.2
1,300	0.8	1.8	4.5	7.2	9.9	0.3	0.5	0.8	1.1	1.3	1.6	1.9	2.1	2.4
1,400	1.1	1.7	4.6	7.5	10.3	0.3	0.6	0.9	1.1	1.4	1.7	2.0	2.3	2.6
1,500	1.5	1.5	4.6	7.7	10.8	0.3	0.6	0.9	1.2	1.5	1.8	2.2	2.5	2.8
+ 1,600	− 2.0	+ 1.3	+ 4.6	+ 7.9	+11.2	0.3	0.7	1.0	1.3	1.6	2.0	2.3	2.6	3.0
1,700	2.4	1.0	4.5	8.0	11.5	0.3	0.7	1.0	1.4	1.7	2.1	2.4	2.8	3.1
1,800	2.9	0.7	4.4	8.1	11.8	0.4	0.7	1.1	1.5	1.8	2.2	2.6	2.9	3.3
1,900	3.5	0.4	4.3	8.1	12.1	0.4	0.8	1.2	1.6	2.0	2.3	2.7	3.1	3.5
2,000	4.1	0.0	4.1	8.2	12.3	0.4	0.8	1.2	1.6	2.1	2.5	2.9	3.3	3.7
+ 2,100	− 4.7	− 0.4	+ 3.8	+ 8.1	+12.5	0.4	0.9	1.3	1.7	2.2	2.6	3.0	3.4	3.9
2,200	5.4	0.9	3.6	8.1	12.6	0.4	0.9	1.3	1.8	2.2	2.7	3.1	3.6	4.0
2,300	6.1	1.4	3.3	8.0	12.7	0.5	0.9	1.4	1.9	2.3	2.8	3.3	3.8	4.2
2,400	6.8	1.9	2.9	7.8	12.7	0.5	1.0	1.5	1.9	2.4	2.9	3.4	3.9	4.4
2,500	7.6	2.5	2.5	7.6	12.7	0.5	1.0	1.5	2.0	2.5	3.0	3.6	4.1	4.6
+ 2,600	− 8.4	− 3.2	+ 2.1	+ 7.4	+12.7	0.5	1.1	1.6	2.1	2.6	3.2	3.7	4.2	4.7
2,700	9.3	3.8	1.6	7.1	12.7	0.5	1.1	1.6	2.2	2.7	3.3	3.8	4.4	4.9
2,800	10.2	4.5	1.1	6.8	12.6	0.6	1.1	1.7	2.3	2.8	3.4	4.0	4.6	5.1
2,900	11.1	5.3	0.6	6.5	12.4	0.6	1.2	1.8	2.3	2.9	3.5	4.1	4.7	5.3
3,000	12.1	6.1	0.0	6.1	12.2	0.6	1.2	1.8	2.4	3.0	3.6	4.3	4.9	5.5
+ 3,100	−13.2	− 6.9	− 0.6	+ 5.7	+12.0	0.6	1.3	1.9	2.5	3.1	3.8	4.4	5.0	5.7
3,200	14.2	7.8	1.3	5.2	11.7	0.6	1.3	1.9	2.6	3.2	3.9	4.5	5.2	5.8
3,300	15.3	8.7	2.0	4.7	11.4	0.7	1.3	2.0	2.7	3.3	4.0	4.7	5.3	6.0
3,400	16.5	9.6	2.7	4.1	11.1	0.7	1.4	2.1	2.8	3.4	4.1	4.8	5.5	6.2
3,500	17.7	10.6	3.5	3.5	10.7	0.7	1.4	2.1	2.8	3.5	4.3	5.0	5.7	6.4
+ 3,600	−18.9	−11.6	− 4.4	+ 2.9	+10.2	0.7	1.5	2.2	2.9	3.6	4.4	5.1	5.8	6.5
3,700	20.1	12.7	5.2	2.2	9.7	0.7	1.5	2.2	3.0	3.7	4.5	5.2	6.0	6.7
3,800	21.4	13.8	6.1	1.5	9.2	0.8	1.5	2.3	3.1	3.8	4.6	5.4	6.1	6.9
3,900	22.8	14.9	7.1	0.8	8.7	0.8	1.6	2.4	3.1	3.9	4.7	5.5	6.3	7.1
4,000	24.2	16.1	8.1	0.0	8.1	0.8	1.6	2.4	3.2	4.0	4.8	5.7	6.5	7.3
+ 4,100	−25.6	−17.3	− 9.1	− 0.8	+ 7.5	0.8	1.7	2.5	3.3	4.1	5.0	5.8	6.6	7.4
4,200	27.0	18.6	10.2	1.7	6.8	0.8	1.7	2.5	3.4	4.2	5.1	5.9	6.8	7.6
4,300	28.5	19.9	11.3	2.6	6.1	0.9	1.7	2.6	3.5	4.3	5.2	6.1	6.9	7.8
4,400	30.1	21.3	12.4	3.6	5.3	0.9	1.8	2.7	3.5	4.4	5.3	6.2	7.1	8.0
4,500	31.6	22.6	13.6	4.6	4.5	0.9	1.8	2.7	3.6	4.5	5.4	6.3	7.2	8.1
+ 4,600	−33.2	−24.0	−14.8	− 5.6	+ 3.7	0.9	1.8	2.8	3.7	4.6	5.5	6.5	7.4	8.3
4,700	34.9	25.5	16.1	6.6	2.8	0.9	1.9	2.8	3.8	4.7	5.7	6.6	7.5	8.5
4,800	36.6	27.0	17.4	7.8	1.9	1.0	1.9	2.9	3.8	4.8	5.8	6.7	7.7	8.7
4,900	38.3	28.5	18.7	8.9	1.0	1.0	2.0	2.9	3.9	4.9	5.9	6.9	7.9	8.8
5,000	40.1	30.1	20.1	10.1	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0
	1,000	2,000	3,000	4,000	5,000	1	2	3	4	5	6	7	8	9

TABLE OF VALUES OF THERMIC TERM, $\frac{A\,(B-A)}{D}$, IN FEET.

a = Approximate Altitude, in Feet.	B = Vertical Base, in Feet.					Additional Hundreds of Feet.								
	6,000	7,000	8,000	9,000	10,000	1	2	3	4	5	6	7	8	9
+ 100	+ 1.2	+ 1.4	+ 1.6	+ 1.8	+ 2.1	0.0	0.0	0.1	0.1	0.1	0.1	0.2	0.2	0.2
200	2.4	2.8	3.2	3.6	4.1	0.0	0.1	0.1	0.2	0.2	0.3	0.3	0.3	0.4
300	3.5	4.2	4.8	5.4	6.1	0.1	0.1	0.2	0.3	0.3	0.4	0.5	0.5	0.6
400	4.6	5.5	6.3	7.1	8.0	0.1	0.2	0.3	0.3	0.4	0.5	0.6	0.7	0.8
500	5.7	6.7	7.8	8.8	9.9	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
+ 600	+ 6.7	+ 7.9	+ 9.2	+10.4	+11.7	0.1	0.2	0.4	0.5	0.6	0.7	0.9	1.0	1.1
700	7.6	9.1	10.6	12.0	13.5	0.1	0.3	0.4	0.6	0.7	0.9	1.0	1.2	1.3
800	8.6	10.2	11.9	13.6	15.3	0.2	0.3	0.5	0.7	0.8	1.0	1.2	1.3	1.5
900	9.4	11.3	13.2	15.1	17.0	0.2	0.4	0.6	0.8	0.9	1.1	1.3	1.5	1.7
1,000	10.3	12.4	14.5	16.6	18.7	0.2	0.4	0.6	0.8	1.0	1.3	1.5	1.7	1.9
+ 1,100	+11.1	+13.4	+15.7	+18.0	+20.3	0.2	0.5	0.7	0.9	1.1	1.4	1.6	1.8	2.1
1,200	11.8	14.3	16.9	19.4	21.9	0.3	0.5	0.8	1.0	1.3	1.5	1.8	2.0	2.3
1,300	12.6	15.2	18.0	20.7	23.4	0.3	0.5	0.8	1.1	1.4	1.6	1.9	2.2	2.4
1,400	13.2	16.1	19.1	22.0	24.9	0.3	0.6	0.9	1.2	1.5	1.8	2.0	2.3	2.6
1,500	13.9	17.0	20.1	23.2	26.4	0.3	0.6	0.9	1.2	1.6	1.9	2.2	2.5	2.8
+ 1,600	+14.4	+17.8	+21.1	+24.4	+27.8	0.3	0.7	1.0	1.3	1.7	2.0	2.3	2.7	3.0
1,700	15.0	18.5	22.1	25.6	29.2	0.4	0.7	1.1	1.4	1.8	2.1	2.5	2.8	3.2
1,800	15.5	19.2	23.0	26.7	30.5	0.4	0.7	1.1	1.5	1.9	2.2	2.6	3.0	3.4
1,900	16.0	19.9	23.9	27.8	31.8	0.4	0.8	1.2	1.6	2.0	2.4	2.8	3.2	3.6
2,000	16.4	20.5	24.7	28.8	33.1	0.4	0.8	1.3	1.7	2.1	2.5	2.9	3.3	3.8
+ 2,100	+16.8	+21.1	+25.5	+29.8	+34.3	0.4	0.9	1.3	1.7	2.2	2.6	3.1	3.5	3.9
2,200	17.1	21.7	26.2	30.8	35.4	0.5	0.9	1.4	1.8	2.3	2.7	3.2	3.7	4.1
2,300	17.4	22.2	26.9	31.7	36.5	0.5	1.0	1.4	1.9	2.4	2.9	3.3	3.8	4.3
2,400	17.7	22.6	27.6	32.6	37.6	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5
2,500	17.9	23.0	28.2	33.4	38.7	0.5	1.0	1.6	2.1	2.6	3.1	3.6	4.2	4.7
+ 2,600	+18.1	+23.4	+28.8	+34.2	+39.7	0.5	1.1	1.6	2.2	2.7	3.2	3.8	4.3	4.9
2,700	18.2	23.8	29.4	35.0	40.6	0.6	1.1	1.7	2.2	2.8	3.4	3.9	4.5	5.0
2,800	18.3	24.1	29.9	35.7	41.5	0.6	1.2	1.7	2.3	2.9	3.5	4.1	4.6	5.2
2,900	18.4	24.3	30.3	36.3	42.4	0.6	1.2	1.8	2.4	3.0	3.6	4.2	4.8	5.4
3,000	18.4	24.5	30.7	36.9	43.2	0.6	1.2	1.9	2.5	3.1	3.7	4.3	5.0	5.6
+ 3,100	+18.3	+24.7	+31.1	+37.5	+44.0	0.6	1.3	1.9	2.6	3.2	3.9	4.5	5.1	5.8
3,200	18.3	24.8	31.5	38.1	44.7	0.7	1.3	2.0	2.6	3.3	4.0	4.6	5.3	5.9
3,300	18.2	24.9	31.8	38.6	45.4	0.7	1.4	2.0	2.7	3.4	4.1	4.8	5.4	6.1
3,400	18.0	25.0	32.0	39.0	46.1	0.7	1.4	2.1	2.8	3.5	4.2	4.9	5.6	6.3
3,500	17.8	25.0	32.2	39.4	46.7	0.7	1.4	2.2	2.9	3.6	4.3	5.1	5.8	6.5
+ 3,600	+17.6	+25.0	+32.4	+39.8	+47.3	0.7	1.5	2.2	3.0	3.7	4.5	5.2	5.9	6.7
3,700	17.3	24.9	32.5	40.1	47.8	0.8	1.5	2.3	3.0	3.8	4.6	5.3	6.1	6.9
3,800	17.0	24.8	32.6	40.4	48.3	0.8	1.6	2.3	3.1	3.9	4.7	5.5	6.3	7.0
3,900	16.7	24.6	32.6	40.7	48.8	0.8	1.6	2.4	3.2	4.0	4.8	5.6	6.4	7.2
4,000	16.3	24.4	32.7	40.9	49.2	0.8	1.6	2.5	3.3	4.1	4.9	5.8	6.6	7.4
+ 4,100	+15.8	+24.2	+32.6	+41.1	+49.5	0.8	1.7	2.5	3.4	4.2	5.1	5.9	6.7	7.6
4,200	15.4	23.9	32.5	41.2	49.9	0.9	1.7	2.6	3.4	4.3	5.2	6.0	6.9	7.8
4,300	14.8	23.6	32.4	41.3	50.2	0.9	1.8	2.7	3.5	4.4	5.3	6.2	7.1	8.0
4,400	14.3	23.3	32.3	41.3	50.4	0.9	1.8	2.7	3.6	4.5	5.4	6.3	7.2	8.1
4,500	13.7	22.9	32.1	41.3	50.6	0.9	1.8	2.8	3.7	4.6	5.5	6.5	7.4	8.3
+ 4,600	+13.1	+22.4	+31.8	+41.3	+50.8	0.9	1.9	2.8	3.8	4.7	5.7	6.6	7.5	8.5
4,700	12.4	21.9	31.5	41.2	50.9	1.0	1.9	2.9	3.8	4.8	5.8	6.7	7.7	8.7
4,800	11.7	21.4	31.2	41.1	51.0	1.0	2.0	2.9	3.9	4.9	5.9	6.9	7.9	8.8
4,900	10.9	20.9	30.9	40.9	51.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0
5,000	10.1	20.3	30.5	40.7	51.0	1.0	2.0	3.1	4.1	5.1	6.1	7.2	8.2	9.2
	6,000	7,000	8,000	9,000	10,000	1	2	3	4	5	6	7	8	9

TABLE OF VALUES OF THERMIC TERM, $\frac{A\,(B-A)}{D}$, IN FEET.

a = Approximate Altitude, in Feet.	B = Vertical Base, in Feet.					Additional Hundreds of Feet.								
	1,000	2,000	3,000	4,000	5,000	1	2	3	4	5	6	7	8	9
+ 5,100	− 41.9	− 31.7	− 21.5	− 11.3	− 1.0	1.0	2.0	3.1	4.1	5.1	6.1	7.2	8.2	9.2
5,200	43.7	33.4	23.0	12.6	2.1	1.0	2.1	3.1	4.2	5.2	6.2	7.3	8.3	9.4
5,300	45.6	35.1	24.5	13.9	3.2	1.1	2.1	3.2	4.2	5.3	6.4	7.4	8.5	9.5
5,400	47.5	36.8	26.0	15.2	4.3	1.1	2.2	3.2	4.3	5.4	6.5	7.6	8.6	9.7
5,500	49.5	38.6	27.6	16.6	5.5	1.1	2.2	3.3	4.4	5.5	6.6	7.7	8.8	9.9
+ 5,600	− 51.5	− 40.4	− 29.2	− 18.0	− 6.8	1.1	2.2	3.4	4.5	5.6	6.7	7.8	9.0	10.1
5,700	53.5	42.2	30.9	19.5	8.0	1.1	2.3	3.4	4.6	5.7	6.8	8.0	9.1	10.3
5,800	55.6	44.1	32.6	21.0	9.3	1.2	2.3	3.5	4.6	5.8	6.9	8.1	9.3	10.4
5,900	57.7	46.0	34.3	22.5	10.7	1.2	2.4	3.5	4.7	5.9	7.0	8.2	9.4	10.6
6,000	59.9	48.0	36.1	24.1	12.1	1.2	2.4	3.6	4.8	6.0	7.2	8.4	9.6	10.8
+ 6,100	− 62.1	− 50.0	− 37.9	− 25.7	−13.5	1.2	2.4	3.7	4.9	6.1	7.3	8.5	9.8	10.9
6,200	64.3	52.0	39.7	27.4	15.0	1.2	2.5	3.7	4.9	6.2	7.4	8.6	9.9	11.1
6,300	66.6	54.1	41.6	29.1	16.5	1.3	2.5	3.8	5.0	6.3	7.5	8.8	10.0	11.3
6,400	68.9	56.2	43.6	30.8	18.0	1.3	2.5	3.8	5.1	6.4	7.6	8.9	10.2	11.4
6,500	71.2	58.4	45.5	32.6	19.6	1.3	2.6	3.9	5.2	6.4	7.7	9.0	10.3	11.6
+ 6,600	− 73.6	− 60.6	− 47.5	− 34.4	−21.2	1.3	2.6	3.9	5.2	6.5	7.9	9.2	10.5	11.8
6,700	76.0	62.8	49.6	36.2	22.9	1.3	2.6	4.0	5.3	6.6	8.0	9.3	10.6	12.0
6,800	78.5	65.1	51.7	38.1	24.6	1.3	2.7	4.0	5.4	6.7	8.1	9.4	10.8	12.1
6,900	81.0	67.4	53.8	− 40.1	. 26.3	1.4	2.7	4.1	5.5	6.8	8.2	9.6	11.0	12.3
7,000	83.5	69.7	55.9	42.0	28.1	1.4	2.8	4.2	5.5	6.9	8.3	9.7	11.1	12.5
+ 7,100	− 86.1	− 72.1	− 58.1	− 44.0	−29.9	1.4	2.8	4.2	5.6	7.0	8.4	9.8	11.2	12.6
7,200	88.7	74.5	60.3	46.1	31.7	1.4	2.8	4.3	5.7	7.1	8.5	10.0	11.4	12.8
7,300	91.3	77 0	62.6	48.1	33.6	1.4	2.9	4.3	5.8	7.2	8.6	10.1	11.5	13.0
7,400	94.0	79.5	64.9	50.3	35.5	1.5	2.9	4.4	5.8	7.3	8.8	10.2	11.7	13.2
7,500	96.7	82.0	67.2	52.4	37.5	1.5	3.0	4.4	5.9	7.4	8.9	10.4	11.8	13.3
+ 7,600	− 99.5	− 84.6	− 69.6	− 54.6	−39.5	1.5	3.0	4.5	6.0	7.5	9.0	10.5	12.0	13.5
7,700	102.3	87.2	72.0	56.8	41.0	1.5	3.0	4.6	6.1	7.6	9.1	10.6	12.1	13.7
7,800	105.1	89.8	74.5	59.1	43.7	1.5	3.1	4.6	6.1	7.7	9.2	10.7	12.3	13.8
7,900	108.0	92.5	77.0	61.4	45.8	1.6	3.1	4.7	6.2	7.8	9.3	10.9	12.4	14.0
8,000	110.9	95.2	79.5	63.8	47.9	1.6	3.1	4.7	6.3	7.9	9.4	11.0	12.6	14.2
+ 8,100	−113.9	− 98.0	− 82.1	− 66.2	−50.1	1.6	3.2	4.8	6.4	8.0	9.6	11.2	12.8	14.4
8,290	116.9	100.8	84.7	68.6	52.3	1.6	3.2	4.8	6.5	8.1	9.7	11.3	12.9	14.5
8,300	119.9	103.6	87.4	71.0	54.6	1.6	3.3	4.9	6.5	8.2	9.8	11.4	13.1	14.7
8,400	122.9	106.5	90.1	73.5	56.9	1.6	3.3	4.9	6.6	8.2	9.9	11.5	13.2	14.8
8,500	126.0	109.4	92.8	76.0	59.3	1.7	3.3	5.0	6.7	8.3	10.0	11.7	13.4	15.0
+ 8,600	−129.2	−112.4	− 95.5	− 78.6	−61.7	1.7	3.4	5.1	6.7	8.4	10.1	11.8	13.5	15.2
8,700	132.3	115.4	98.3	81.2	64.1	1.7	3.4	5.1	6.8	8.5	10.2	11.9	13.6	15.3
8,800	135.5	118.4	101.2	83.9	66.5	1.7	3.4	5.2	6.9	8.6	10.3	12.1	13.8	15.5
8,900	138.8	121.4	104.1	86.6	69.0	1.7	3.5	5.2	7.0	8.7	10.5	12.2	14.0	15.7
9,000	142.1	124.5	107.0	89.3	71.6	1.8	3.5	5.3	7.0	8.8	10.6	12.3	14.1	15.9
+ 9,100	−145.4	−127.7	−109.9	− 92.1	−74.2	1.8	3.6	5.3	7.1	8.9	10.7	12.5	14.2	16.0
9,200	148.7	130.8	112.9	94.9	76.8	1.8	3.6	5.4	7.2	9.0	10.8	12.6	14.4	16.2
9,300	152.1	134.0	115.9	97.7	79.4	1.8	3.6	5.4	7.3	9.1	10.9	12.7	14.5	16.4
9,400	155.6	137.3	119.0	100.6	82.1	1.8	3.7	5.5	7.4	9.2	11.0	12.9	14.7	16.6
9,500	159.0	140.6	122.1	103.5	84.8	1.9	3.7	5.6	7.4	9.3	11.1	13.0	14.8	16.7
+ 9,600	−162.5	−143.9	−125.2	−106.4	−87.6	1.9	3.7	5.6	7.5	9.4	11.2	13.1	15.0	16.9
9,700	166.1	147.2	128.4	109.4	90.4	1.9	3.8	5.7	7.6	9.5	11.4	13.2	15.1	17.0
9,800	169.6	150.6	131.6	112.4	93.2	1.9	3.8	5.7	7.6	9.5	11.5	13.4	15.3	17.2
9,900	173.2	154.1	134.8	115.5	96.1	1.9	3.9	5.8	7.7	9.6	11.6	13,5	15.4	17.4
10,000	176.9	157.5	138.1	118.6	99.0	1.9	3.9	5.8	7.8	9.7	11.7	13.6	15.6	17.5
	1,000	2,000	3,000	4,000	5,000	1	2	3	4	5	6	7	8	9

TABLE OF VALUES OF THERMIC TERM, $\frac{A\,(B-A)}{D}$, IN FEET.

a = Approximate Altitude, in Feet.	B = Vertical Base, in Feet.					Additional Hundreds of Feet.								
	6,000	7,000	8,000	9,000	10,000	1	2	3	4	5	6	7	8	9
+5,100	+ 9.3	+19.6	+30.1	+40.5	+51.0	1.0	2.1	3.1	4.2	5.2	6.3	7.3	8.3	9.4
5,200	8.4	19.0	29.6	40.2	50.9	1.1	2.1	3.2	4.2	5.3	6.4	7.4	8.5	9.6
5,300	7.5	18.3	29.1	39.9	50.8	1.1	2.2	3.2	4.3	5.4	6.5	7.6	8.7	9.7
5,400	6.6	17.5	28.5	39.5	50.6	1.1	2.2	3.3	4.4	5.5	6.6	7.7	8.8	9.9
5,500	5.6	16.7	27.9	39.1	50.4	1.1	2.2	3.4	4.5	5.6	6.7	7.8	9.0	10.1
+5,600	+ 4.5	+15.9	+27.3	+38.7	+50.2	1.1	2.3	3.4	4.6	5.7	6.9	8.0	9.1	10.3
5,700	3.5	15.0	26.6	38.2	49.9	1.2	2.3	3.5	4.6	5.8	7.0	8.1	9.3	10.4
5,800	2.4	14.1	25.9	37.7	49.6	1.2	2.4	3.5	4.7	5.9	7.1	8.3	9.4	10.6
5,900	1.2	13.1	25.1	37.1	49.2	1.2	2.4	3.6	4.8	6.0	7.2	8.4	9.6	10.8
6,000	0.0	12.1	24.3	36.5	48.8	1.2	2.4	3.7	4.9	6.1	7.3	8.5	9.8	11.0
+6,100	− 1.2	+11.1	+23.5	+35.9	+48.3	1.2	2.5	3.7	4.9	6.2	7.4	8.7	9.9	11.2
6,200	2.5	10.0	22.6	35.2	47.8	1.3	2.5	3.8	5.0	6.3	7.5	8.8	10.1	11.3
6,300	3.8	8.9	21.7	34.5	47.3	1.3	2.6	3.8	5.1	6.4	7.7	8.9	10.2	11.5
6,400	5.2	7.7	20.7	33.7	46.8	1.3	2.6	3.9	5.2	6.5	7.8	9.1	10.4	11.7
6,500	6.6	6.5	19.7	32.9	46.1	1.3	2.6	3.9	5.3	6.6	7.9	9.2	10.5	11.9
+6,600	− 8.0	+ 5.3	+18.7	+32.1	+45.5	1.3	2.7	4.0	5.4	6.7	8.0	9.4	10.7	12.0
6,700	9.4	4.0	17.6	31.2	44.8	1.4	2.7	4.1	5.4	6.8	8.1	9.5	10.8	12.2
6,800	10.9	2.7	16.5	30.3	44.1	1.4	2.7	4.1	5.5	6.9	8.2	9.6	11.0	12.4
6,900	12.5	1.4	15.3	29.3	43.3	1.4	2.8	4.2	5.6	7.0	8.4	9.8	11.2	12.6
7,000	14.1	0.0	14.1	28.3	42.5	1.4	2.8	4.2	5.7	7.1	8.5	9.9	11.3	12.7
+7,100	−15.7	+ 1.5	+12.9	+27.2	+41.7	1.4	2.9	4.3	5.7	7.2	8.6	10.0	11.5	12.9
7,200	17.3	2.9	11.6	26.2	40.8	1.5	2.9	4.4	5.8	7.3	8.7	10.2	11.6	13.1
7,300	19.0	4.4	10.3	25.0	39.9	1.5	2.9	4.4	5.9	7.4	8.8	10.3	11.8	13.3
7,400	20.8	6.0	8.9	23.9	38.9	1.5	3.0	4.5	6.0	7.5	9.0	10.4	11.9	13.4
7,500	22.6	7.6	7.5	22.7	37.9	1.5	3.0	4.5	6.0	7.6	9.1	10.6	12.1	13.6
+7,600	−24.4	− 9.2	+ 6.1	+21.4	+36.8	1.5	3.1	4.6	6.1	7.7	9.2	10.7	12.2	13.8
7,700	26.2	10.8	4.6	20.2	35.7	1.5	3.1	4.6	6.2	7.7	9.3	10.8	12.4	13.9
7,800	28.1	12.5	3.1	18.8	34.6	1.6	3.1	4.7	6.3	7.8	9.4	10.9	12.5	14.1
7,900	30.0	14.3	1.6	17.5	33.5	1.6	3.2	4.8	6.3	7.9	9.5	11.1	12.7	14.3
8,000	32.0	16.0	0.0	16.1	32.3	1.6	3.2	4.8	6.4	8.0	9.6	11.2	12.9	14.5
+8,100	−34.0	−17.8	− 1.6	+14.7	+31.0	1.6	3.2	4.9	6.5	8.1	9.7	11.4	13.0	14.6
8,200	36.0	19.7	3.3	13.2	29.7	1.6	3.3	4.9	6.6	8.2	9.9	11.5	13.1	14.8
8,300	38.1	21.6	5.0	11.7	28.4	1.7	3.3	5.0	6.6	8.3	10.0	11.6	13.3	15.0
8,400	40.2	23.5	6.7	10.1	27.1	1.7	3.4	5.0	6.7	8.4	10.1	11.8	13.5	15.1
8,500	42.4	25.5	8.5	8.5	25.7	1.7	3.4	5.1	6.8	8.5	10.2	11.9	13.6	15.3
+8,600	−44.6	−27.5	−10.3	+ 6.9	+24.2	1.7	3.4	5.2	6.9	8.6	10.3	12.0	13.8	15.5
8,700	46.8	29.6	12.2	5.2	22.7	1.7	3.5	5.2	6.9	8.7	10.4	12.2	13.9	15.7
8,800	49.1	31.7	14.1	3.5	21.2	1.7	3.5	5.3	7.0	8.8	10.5	12.3	14.1	15.8
9,900	51.4	33.8	16.0	1.8	19.7	1.8	3.5	5.3	7.1	8.9	10.6	12.4	14.2	10.0
9,000	53.8	35.9	18.0	0.0	18.1	1.8	3.6	5.4	7.2	9.0	10.8	12.6	14.4	16.2
+8,100	−56.2	−38.1	−20.0	− 1.8	+16.4	1.8	3.6	5.4	7.3	9.1	10.9	12.7	14.5	16.3
9,200	58.6	40.4	22.1	3.7	14.8	1.8	3.7	5.5	7.3	9.2	11.0	12.8	14.7	16.5
9,300	61.0	42.7	24.2	5.6	13.1	1.9	3.7	5.6	7.4	9.3	11.1	13.0	14.8	16.7
9,400	63.5	45.0	26.3	7.5	11.8	1.9	3.7	5.6	7.5	9.3	11.2	13.1	15.0	16.8
9,500	66.1	47.3	28.4	9.5	9.5	1.9	3.8	5.7	7.6	9.4	11.3	13.2	15.1	17.0
+9,600	−68.7	−49.7	−30.6	−11.5	+ 7.7	1.9	3.8	5.7	7.6	9.5	11.5	13.4	15.3	17.2
9,700	71.3	52.1	32.9	13.6	5.8	1.9	3.8	5.8	7.7	9.6	11.6	13.5	15.4	17.3
9,800	73.9	54.6	35.2	15.7	3.9	1.9	3.9	5.8	7.8	9.7	11.7	13.6	15.6	17.5
9,900	76.6	57.1	37.5	17.8	2.0	2.0	3.9	5.9	7.9	9.8	11.8	13.8	15.7	17.7
10,000	79.4	59.6	39.8	20.0	0.0	2.0	4.0	6.0	7.9	9.9	11.9	13.9	15.9	17.9
	6,000	7,000	8,000	9,000	10,000	1	2	3	4	5	6	7	8	9

SUPPLEMENTARY NOTE

ON THE ELIMINATION OF THE INFLUENCE OF WIND PRESSURE FROM BAROMETRIC OBSERVATIONS.

One result of the inquiry detailed in Chapter IV was the discovery that the pressure of the wind introduced a large error into the series of barometric observations made on Mount Washington in June, 1873. A northwest wind of 50 miles per hour, by drawing air out of the observatory (presumably through the chimney), caused the mercury in the barometer to stand .13 inch too low. Since the power of the wind to produce such effects is proportional, not to its simple velocity, but to the square of its velocity, it is evident that such a wind as the strongest observed at that station may utterly vitiate the record of the barometer. A wind with a velocity of 100 miles per hour would, under the same conditions, depress the barometer more than half an inch; and, after making every allowance for inaccuracy of velocity determinations, it cannot be doubted that that station is frequently subjected to a wind of that speed. In hypsometry, a barometric error of one half inch affects the computed height 500 feet. In the plotting of isobaric maps, such as are daily prepared by the Weather Bureau of the Army, it displaces five of the curves, putting them on the wrong side of the station where the error is incurred, and correspondingly distorting the contours of storms.

Not all winds had this effect at Mount Washington. Perhaps none do in the present observatory, for the building now occupied is not the one in use in June, 1873. But the danger certainly exists, and it is incurred by all stations subject to high winds. If any such errors occur, even though comparatively small, they cannot fail both to retard the development of the science of storms and to add to the uncertainty of meteorologic prediction. It is therefore important that the difficulty be thoroughly met. How shall this be done?

It is safe to say that it cannot be met by merely applying a correction to the reading of the barometer without attempting to control the conditions to which it is exposed. To make such a correction efficacious, we should need to know not simply the general influence of the wind upon the tension of the air in each room used as a meteorologic observatory, but the special influence of each particular wind, and this knowledge would be in the highest degree difficult to obtain. If we had some standard for comparison it would be possible to observe the actual errors at each observatory, and from them to construct a table of corrections

applicable to the readings of the barometer; but while the wind blows, one barometer is as much a standard as another, since no room can be known to be exempt from the disturbing influence.

It follows that the conditions must be controlled. We must bring special apparatus to our aid and put the barometer in such relation to the wind that it will either record the normal pressure or else deviate from it by an ascertainable amount.

Three types of apparatus suggest themselves, each of which incloses the barometer in an air-tight case and connects the interior of the case with the outer air by means of a tube, the open end of which is made to assume a definite relation to the wind. If we exclude oblique positions from consideration, there are three relations which may be assumed by the tube. The aperture may be turned toward the wind (*a* in the diagram), it may be turned from the wind (*c*), or it may be directed at right angles to the course of the wind (*b*). It is evident that the wind will force air into the tube *a*, and thus increase the tension within the tube; it is evident that it will draw air out of the tube *c*, and thus diminish the tension within; and it has been shown by the experiments of Magius and Hagemann[*] that air is drawn also from the tube *b*, so as to produce a diminution of tension. The increase of tension in the tube *a* is equal to the horizontal force of the wind. Hagemann's experiments indicate that the decrease of tension in the tube *b* is likewise equal to the force of the wind, but his demonstration is indirect, and perhaps should not be accepted without further experiment. The tension in the tube *c* has not been investigated, but it is *a priori* probable that its deficiency as compared with the normal tension is equal to the excess produced in the tube *a*.

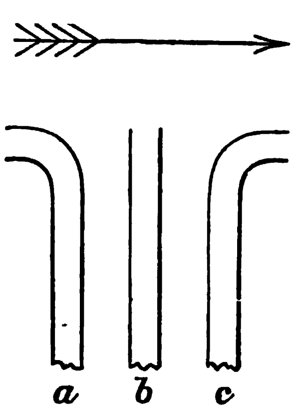


FIG. 32.—Diagram showing Relations of Tube Apertures to Wind. The Arrow points the Direction toward which the Wind is supposed to Blow.

The first suggested apparatus is as follows: Insulate a barometer from the air tension of the observatory, either by encasing the instrument or by encasing its cistern, and establish a communication with the outer air by means of a tube exposed to the wind in one of the three indicated ways. If the tube *b* is selected, it will need merely to be directed upward and so placed with reference to surrounding objects that it will be exposed to none but horizontal air currents. If *a* or *c* is used, it must be joined to a vane in such way as to maintain a constant relation to the direction of the wind. Whichever tube is employed, there must be placed near it an anemometer of some sort. If the tube *a* is used, the pressure indicated by the barometer will be greater than

[*] See reference on page 533.

the normal pressure; if *b* or *c* is used, it will be less than the normal; and in either case the correction necessary to be applied to the reading in order to deduce the normal pressure will be derivable from the velocity or pressure of the wind, as given by the anemometer.

The second suggested apparatus uses two barometers instead of one, and discards the anemometer. The barometers are independently inclosed. One of them is exposed to the wind by means of a tube of the form *a*, and gives a reading too high; the other is exposed to the wind by means of a tube like *b* or *c*, and gives a reading too low. The true reading, or the normal pressure, is evidently a function of the two abnormal readings, and is derivable from them.

The difference between the two readings depends upon the force of the wind, and may be made to serve as its measure. The second apparatus might therefore be used also as an anemometer.

In the third suggested apparatus a single barometer is made to communicate with the outer air by means of two or more apertures. Let us suppose that the tubes *a* and *c* are connected at bottom with a box which is otherwise closed. The wind forces the air into the box through the tube *a*, and draws it from the box through the tube *c*. The tendency of the inflowing air is to increase the tension in the box; the tendency of the outflowing air is to diminish it; and it is conceivable that the tubes can be so adjusted in size and form that the two influences shall neutralize each other, whatever the velocity of the wind, and leave a normal tension in the box. If this can be done, then a barometer put in communication with the box will record the normal atmospheric pressure, and its indication will require no correction.

Neither apparatus can be qualified for its work without a preliminary series of experiments, but there seems no reason to question that, with suitable details, either of them may be made to serve the purpose. A number of precautions and mechanical devices have occurred to the writer, which need not be described, because they will readily suggest themselves to any competent person who undertakes the experimentation necessary to the development of an apparatus.

It is to be observed that the third plan is the only one which promises any relief to the itinerary observer, and that the best relief it can possibly afford is but partial. And this leads to the further observation that the disturbing influence of the wind is two-fold, and that only one factor of it can be counteracted by apparatus. Besides the abnormal tensions communicated to apartments through apertures, there is another set of abnormal tensions, arising wherever the wind blows across an uneven surface. We may imagine that a level plain swept by a wind may sustain an equal pressure on every part, but if the continuity of the plain be interrupted by any projecting object, such as a hill or a house, an inequality of tension is produced. The atmospheric tension and pressure upon the windward side of the obstruction become abnormally great, and upon the lee side abnormally small. This is an ine-

quality dependent upon locality, and cannot be corrected by mechanical appliances. Theoretically, there seems no way to avoid it except by the selection of localities for observation, and that selection is a matter of difficulty. A fixed observatory is itself an obstruction to the wind, and even if there are no other buildings in its vicinity it must be surrounded during a strong wind by a system of abnormal tensions. The mountain peak upon which the geographer has so frequently to read his barometer, and upon which he so often encounters a strong wind, is an obstruction of the most prominent kind. If he hangs his barometer on the windward side of the summit, he can be sure that his reading will be too high; if on the leeward side, that it will be too low; but there seems no possible way of selecting for observation a point subject to the normal pressure.

POSTSCRIPT ON GRAPHIC TABLE.

In the application of the table for the thermic correction, pages 556–561, a double interpolation is frequently necessary; and a double interpolation is always inconvenient. It is especially irksome in this case because the total value of the correction is so small as compared with the altitude it modifies. An attempt has therefore been made to avoid it by the construction of a graphic table, but the latter was not completed in time for the first edition of the volume. It is here added in Plate LXII, and a few words are necessary in explanation.

Vertical distances in the graphic table represent heights of base line, or values of B in the formula. Their origin or zero is at the base of the diagram. A horizontal line is drawn at each hundred feet, and a stronger line at each thousand feet. The thousand-feet marks are numbered at the right.

Horizontal distances represent values (in feet) of the approximate altitude—*a* of the formula—and each hundred feet is indicated by a vertical line. The zero line, or the origin of horizontal distances, is not at the margin of the diagram, but is between the middle and the right-hand margin, as indicated by the numbering at the bottom. Distances to the left of this line represent positive values of the approximate altitude, and distances to the right represent negative values thereof. The positive values run from 0 to 8,000 feet, the negative from 0 to 3,000 feet.

Upon this reticle of straight lines a system of curves is drawn, and each curve represents a value of the thermic correction or thermic term, $\frac{A\,(B-A)}{490000}$ of the formula. The curve which falls nearest to the zero line of approximate altitudes corresponds to a correction of $\frac{1}{2}$ foot, the curve next it to a correction of $1\frac{1}{2}$ feet, the third to $2\frac{1}{2}$ feet, etc. For

every point between the first and second curves the correction is greater than ½ foot and less than 1½ feet, or, if fractions are disregarded, it is 1 foot. So, for all points falling in the next space the correction is 2 feet, etc. The numbers on the upper and left hand margins apply to these spaces and show the values of the thermic correction corresponding to them. They are written opposite every fifth space, and the corresponding spaces are given a tint for convenience in tracing across the page.

EXAMPLE ILLUSTRATING USE OF TABLE.

When B = 7,210 feet and $a = +2,570$ feet, required the value of the thermic correction.

First, find by the aid of the right-hand index the horizontal line corresponding to 7,200 feet, then from the index at the base the line corresponding to +2,600 feet. Trace them to their intersection. By inspection determine a point $\frac{1}{10}$ of the ruled square above this intersection and $\frac{3}{10}$ of the ruled square to the right of it. This point indicates the intersection of the undrawn lines representative of the arguments 7,210 feet and 2,570 feet. Note the relation of this point to the curved spaces; the space containing it is next to one of the tinted spaces. Tracing the tinted space in either direction to the margin of the diagram its index is found to be +25 feet, and the index of the space next it is therefore +24 feet—the desired thermic correction.

If this same example were solved by means of the table on page 559 the value 24.3 feet would be obtained, but the refinement implied by the definition of the tenths of a foot is a useless one, as has already been explained on page 450.

The computer who has to determine a large number of new stations by reference to a single pair of base stations, will find it advantageous to draw upon the graphic table a horizontal red line representative of his particular value of B. He will thus produce with a minimum of effort a one-argument table equivalent to that recommended on page 555.

This graphic table is in some sense an experiment. The idea, indeed, is not novel, but it has not been widely applied. It appears to the writer that a similar plan might advantageously be adopted for the tabulation of factors dependent upon two arguments whenever the arguments are large as compared with the tabulated factor; or rather, whenever the number of digits used to express each argument is large as compared with the number of digits used to express the dependent factor.

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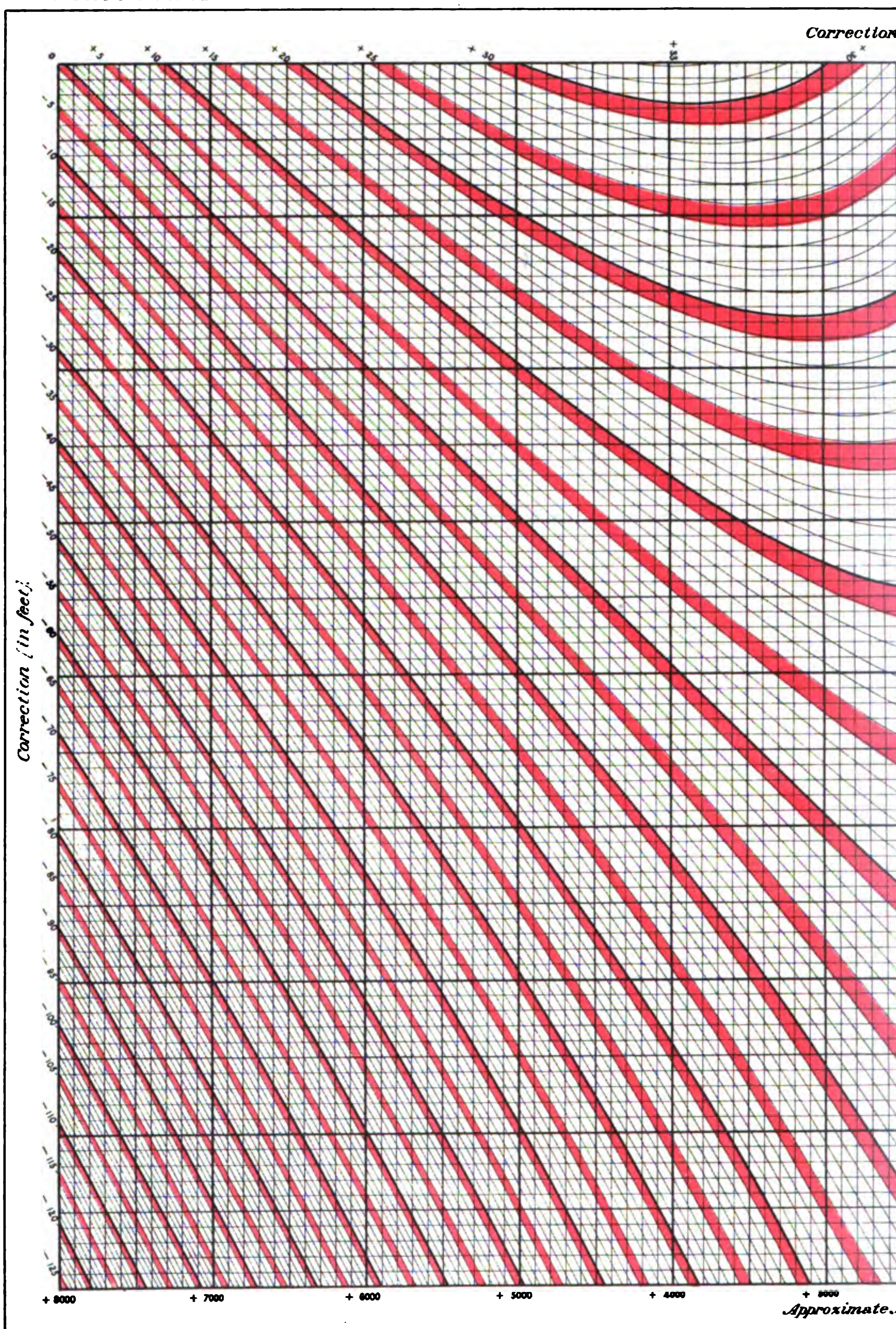

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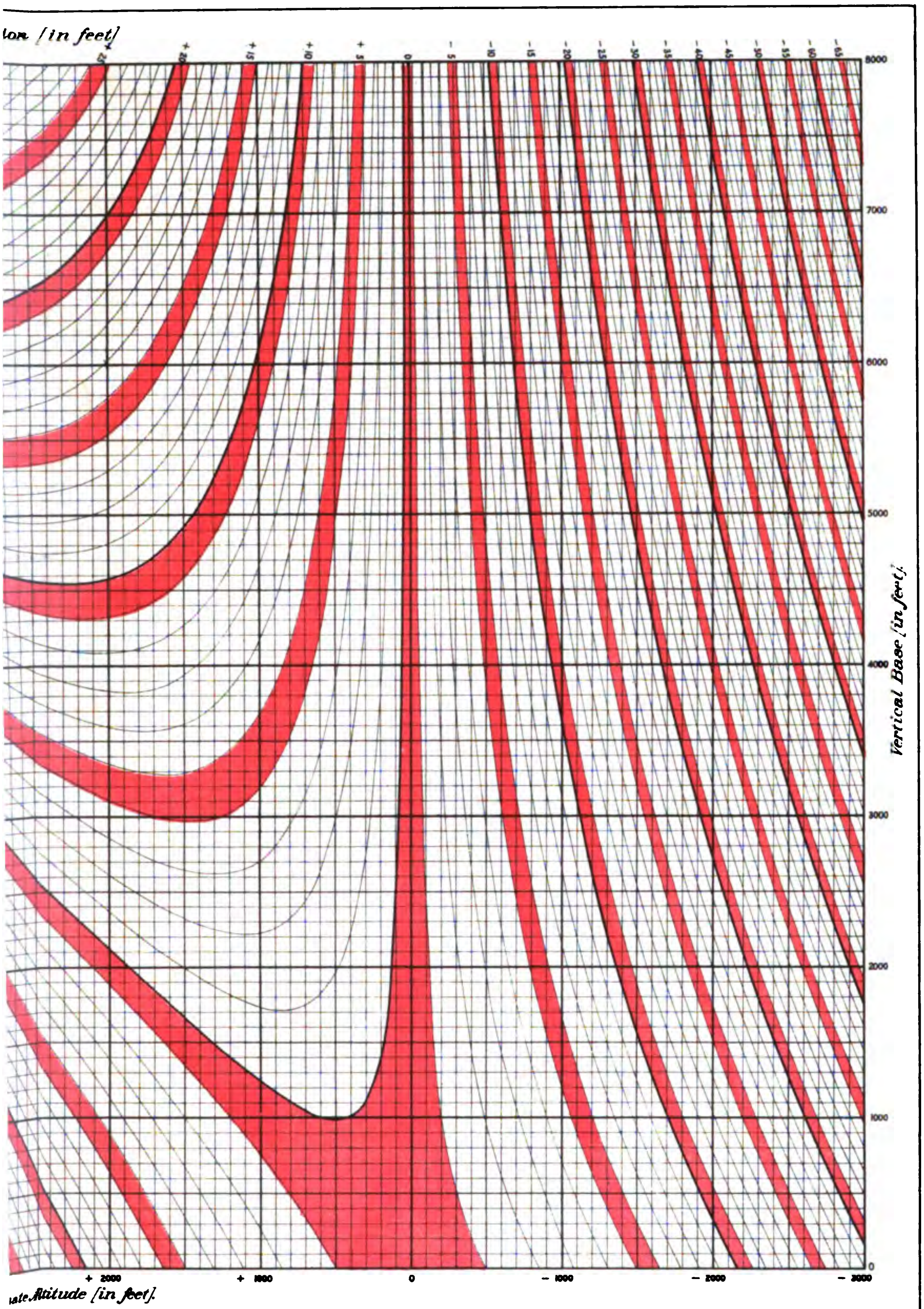

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GEOLOGY

OF THE

CAPE COD DISTRICT

BY

NATHANIEL S. SHALER

EXTRACT FROM THE EIGHTEENTH ANNUAL REPORT OF THE SURVEY, 1896-97
PART II—PAPERS CHIEFLY OF A THEORETIC NATURE

WASHINGTON
GOVERNMENT PRINTING OFFICE
1898

GEOLOGY OF THE CAPE COD DISTRICT.

BY

N. S. SHALER.

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CONTENTS.

ILLUSTRATIONS.

GEOLOGY OF THE CAPE COD DISTRICT.

By N. S. Shaler.

INTRODUCTORY NOTE.

It was at first intended that this paper should include the geology of the peninsula of Cape Cod only, but the progress of the work has made it necessary to extend the consideration so as to take some account of the structure and the succession of deposits exhibited in portions of the mainland, as well as on the islands to the southward. The progress of the inquiry has made it necessary to limit the scope of the work to a somewhat extended discussion of the evidence that goes to show the series of geological events which have occurred in this district since the beginning of the Cretaceous period. Such of the facts as pertain to this discussion are given in this paper; further details will be set forth in the geological folios of the area, which it is expected will shortly be ready for the press.[1]

Inquiries in this field have been very limited in their number and range. Those instituted by the United States Geological Survey have resulted in a Report on the Geology of Marthas Vineyard, in the Seventh Annual Report of the Director (for 1885–86); a report on The Geology of Nantucket, being Bulletin No. 53 (1889) of the Survey series (both by the writer of this paper); a report on The Glacial Brick Clays of Rhode Island and southeastern Massachusetts, by N. S. Shaler, J. B. Woodworth, and C. F. Marbut, in Part I of the Seventeenth Annual Report of the Survey (for 1895–96); and the unpublished folios above referred to.

The reader of the above-named published reports and of this paper will perceive that the Cape Cod district has unexpectedly revealed a considerable range of phenomena, the discussion of which is certain to throw much light on the geological history of the Atlantic coast line. Unfortunately the evidence concerning the succession of these phenomena is of a very obscure nature, and it is therefore not surprising that in the reports above referred to some of it was misapprehended and much was not discerned. Nor must it be supposed that in the following pages anything like a final statement of the facts or of the conclusions to be drawn from them is to be found. Such a statement can not be expected until investigation has gone much further.

I take pleasure in acknowledging indebtedness to Mr. J. B. Woodworth for advice in some parts of the work, and to Messrs. Mark S. W. Jefferson and John Gardner for help in obtaining the photographs from which the illustrations are taken.

[1] Folios of the Geologic Atlas of the United States.

ORIGIN OF CAPE COD PENINSULA.

The origin and structure of the peninsula of Cape Cod have been a matter of passing interest to all who have considered the geology of the southeastern portion of New England. The peculiar spit-like form of this promontory was at first, and naturally, supposed to be accounted for by the action of the marine currents to which are due the construction of so many of the lesser capes along this portion of the Atlantic shore. When it became evident that a large portion of the materials composing the higher parts of the cape had been brought into position by the action of ice during the last Glacial period, the spit theory was abandoned, and it was at once assumed that the greater part of this area owed its existence as dry land to the morainal and stratified drift deposits which are so evident on the surface, the northeastern extremity being a later addition, made by the action of marine waves and currents.

The last-noted hypothesis as to the origin of Cape Cod, by glacial action, long appeared to have much support from the view, so generally entertained, that the outer morainal deposits formed during the advance of the ice were likely to be massive and of great extent; so that it thus seemed reasonable to suppose that the portion of this cape that was evidently not due to marine agencies was accumulated as a frontal moraine. An inspection of this field alone, without the use of corrections which may be obtained from other parts of the country, almost necessarily leads the observer to adopt the view last mentioned. It was not until I had seen much of the morainal deposits of the region between the Cordilleras and the Atlantic shore, and had made a study of the relations of those accumulations to the Tertiary and Cretaceous rocks of Marthas Vineyard, Nantucket, and other parts of the Atlantic coast line between southern New Jersey and Boston Bay, that I gained what seemed to me to be a truer insight into the nature of the singular peninsula of Cape Cod. On this account it appears desirable to preface the study of this district by an account of the facts revealed in neighboring fields which seem to throw light on its problems.

GENERAL RELATIONS OF THE DISTRICT.

A glance at a map of the eastern shore of North America will show that the peninsula of Cape Cod is in some respects the most peculiar feature of this coast line; geographically considered, it is in a high measure exceptional. Its crescentic form, as before remarked, is by no means unique, except as to the great size of the hook, many of the sand spits imitating in a small way the general coastal outline of this peninsula; but in the bold manner in which this salient projects from the shore, in its strong topographical relief, and in the character of its coast line, it finds no parallel, so far as I have been able to ascertain, in any country. This exceptional geographical character naturally leads an observer who is aware of the indicative value of such features to

seek the origin of this cape in conditions of an unusual sort, such as will become apparent in a discussion of the general relations of the district.

It has long been known that the Cretaceous and Tertiary deposits so extensively developed in the southern portion of the Atlantic States of this country are continued in an interrupted belt lying to the east of the more ancient rocks as far north as southeastern Massachusetts, the Cretaceous extending up to the deposits on Marthas Vineyard and the Miocene Tertiary reaching to Marshfield, a point some distance north of the northern border of Cape Cod. Associated with these Mesozoic and Cenozoic deposits are extensive series of stratified sands and gravels which have hitherto been commonly classified with the glacial drift. South of New York these beds show little signs of disturbance by orogenic action; such distortions as have been noticed in the beds can apparently in most cases be explained by accidents of deposition. North of New York, on Long Island and in the isles to the eastward, these beds have been subjected to dislocation, which in Marthas Vineyard becomes profound, so far as is indicated by the attitude of the beds, exceeding on the average the distortions of the Appalachian Mountain district or of the neighboring field of the Narragansett Basin.

Certain observers have sought to account for the dislocations of these newer rocks on the New England shore district by supposing them to be due to the action of the glaciers of the last ice epoch. As I have elsewhere noted, this view seems quite inadmissible, for the reason that the uplifting and folding of the beds took place long before the advent of the last ice epoch. As this point is of much importance in the discussion of the problem as to the origin of Cape Cod, it will be well to present the facts in some detail, especially as certain excavations recently made on Marthas Vineyard have somewhat extended our knowledge concerning the history of the glacial work in that field.

On Marthas Vineyard the Cretaceous and Tertiary strata, exhibiting a total section of probably 1,000 feet or more, are cast into folds of considerable amplitude, some of them apparently exceeding 1,500 feet in transverse extent. These folds are compressed, overturned, and faulted; in a word, they exhibit all the marks of mountain-building actions working on stratified deposits of weak resistance to compression and not deeply buried. So general and effective has this dislocation been that it has involved all the rocks which are exposed to view, the average dip of the strata perhaps exceeding 40 degrees.

In these exceedingly disturbed strata river valleys were excavated which had their position determined in the usual manner, the greater streams following in general the strike of the beds, the lesser—those occupied by the temporary streams—running at right angles thereto. The larger of these valleys, that of Tisbury River, is about one-third of a mile wide and more than 100 feet deep. Upon this normal and well-developed topography, which indicates a continuance of stream erosion that must have occupied a period to be measured by tens of

thousands of years, came the glacier of the last ice epoch. I have elsewhere[1] noted the fact that this ice sheet had little erosional effect upon the topography of this island, and the impression made by my first studies has been confirmed by recent inquiries in the same field. The facts may be briefly stated as follows:

The ice sheet failed to obliterate many details of the topography which were due to differential erosion before the advent of the glacier. At many points the ridges of harder rock, though at most no firmer than compacted sand or soft clay, stand evidently as they were originally formed. So imperfectly did the ice abrade the surface that the white and red colors of the clays is rarely traceable to a height of a foot above the contact of the till with the underlying beds. Although along the crests of the greater ridges there are morainal accumulations which have in places a thickness of from 20 to 50 feet, these are limited to the northern side of the island; the southern part has only slight moraines. Over nearly one-half the area in which the Cretaceous and Tertiary strata rise above the level of the sea the till coating does not average 3 feet in thickness, and many fields of a hundred acres or more in extent are essentially driftless. On the southern shore the evidence at present afforded by the rapidly retreating cliffs is to the effect that a deeply incised topography formed in the Nashaquitsa clays was not effaced, the sharp valleys being merely filled in with the drift deposits. In a word, the conditions of this area indicate that the glacier of the last ice epoch was of such slight dynamic value that it produced little erosion and that all the important dislocatory work was done long before it came upon the district.

It is to be said that there is some evidence of ice action shown by the character of the latest-formed deposits of the disturbed strata, seen in the presence in one of the conglomerates exhibited at Gay Head of pebbles and bowlders apparently derived from the region of Narragansett Bay, including one fragment of the very characteristic ilmenite from Iron Hill, in the town of Cumberland, Rhode Island. But this ice period of the Pliocene or Pleistocene time was, if it existed, so far as we can discern, an even less effective invasion than that of the last Glacial epoch, and, as it came before the dislocation of the beds, can not possibly be made to account for their disturbance. There is thus no reason to doubt that the extensive stress phenomena of this field must be explained by supposing that they are in some way the result of orogenic action. We are, indeed, justified in assuming that along the section of the shore line extending, it may be, from western Long Island to the island of Nantucket, mountain-building movements involving stresses of considerable intensity have been developed.

As to the operation of these mountain-building actions in the district of Cape Cod, the evidence, though not perfectly clear, leads to the

[1] Report on the geology of Marthas Vineyard; Seventh Ann. Rept. U. S. Geol. Survey, 1885–86 (1888), p. 310.

conclusion that they worked on the ill-disclosed foundations of that peninsula in much the same manner that they have done in the well-exhibited beds of Marthas Vineyard. As will be noted in the sequel, the strata which are known on Cape Cod include nothing below the level of the Nashaquitsa series as described in the report on Marthas Vineyard; but the presence of the Tertiary greensands at Marshfield causes the presumption that beds of earlier age lie within the peninsula.

The limited extent of the exposures of the foundation materials of Cape Cod makes it desirable to take into account the structure and history of the adjacent areas both on the south and on the north. It is, indeed, necessary to do this in order to arrive at an understanding as to the history of the particular area. This consideration should include the origin of the sediments, the nature of the transporting agents which brought them to their sites, the orogenic accidents, the development of the drainage, and the oscillations of the sea level which have taken place on this portion of the shore.

The sediments of the Cretaceous and Tertiary rocks in the district between Washington and Boston exhibit certain peculiarities which are not found elsewhere in the eastern United States. The section is in part made up of colored clays and sands, which, except for the admixture of peaty matter in the lignite beds, are evidently derived from the rapid deposition of land waste washed from an area which had been long subjected to interstitial decay, which was followed by rapid erosion. In the lower portion of the beds the conditions are not so abnormal, the clays and sands in general resembling those of the Southern States. They appear to have been deposited from the discharge into the sea of ordinary rivers. The structure of the lignites, which, so far as observed, contain much clay, indicates that they were formed in an estuarine district, subjected to frequent floodings of muddy water and to slight subsidences, which permitted the peaty accumulations to be buried beneath silt.

In passing to the higher marine strata, we find at once that we are in very different clastic conditions. The beds in the Marthas Vineyard district consist of alternating clays and sands, which have evidently been deposited in a rapid manner. The clays show scarcely a trace of lamination, and the sands are exceedingly coarse, often being made up of bits of decayed granite, the crystals running together in one mass. Much of the deposit is composed of detached, not rounded, crystals of feldspar, which are so far softened by decay that they can be crushed in the fingers. It is, in a word, a true arkose, lacking only the usual consolidation of that material, and so destitute of admixture of such substances as are inevitably brought into detrital beds where the transportation which bore the waste to its resting place was by rivers or shore currents, that a careful study of sections many square yards in area has failed to show a trace of any other material than the broken-up crystalline rock from which it was derived.

After passing up through a section having a total thickness of several hundred feet in which the above-noted alternations are exhibited, we come suddenly to a level where beds of conglomerate, composed of ordinary compound hypogene rocks, occur in pebbles of moderate size not differing much in character from those formed during the last Glacial period, except that they are more decayed and somewhat more waterworn. Yet higher in the section we attain to the Nashaquitsa series, which are also somewhat dislocated. These are beds of sands and clays, in general character like those formed during the last Glacial period, though on account of their greater age they have been much more changed in texture than those of that epoch. The interpretation of this section is difficult. The most probable explanation is that which will now be set forth.

In the first place, we may note the fact that the shore line of the old crystalline district of the Appalachians appears always to have lain near this seat of deposition. The arkose in the Tertiary shows this to have been the case in that period. It was so again at the time of the higher conglomerate, and the character of the clays and arkose beds shows that they were not offshore deposits. The structure of these beds suggests that they were laid down in a swiftly accumulated delta at the mouth of a river, which might well have been a continuation of the Connecticut.

The lower Cretaceous deposits, being in nature such as would be discharged from streams draining a land subjected to ordinary conditions of erosion, demand no special explanation. As before noted, it is quite evident that the rocks beneath the land from which they came had been deeply decayed in a long period of stable conditions, such as has prevailed in the southern Appalachians. Suddenly this zone of decay was to a great extent swept away into the neighboring sea, the process continuing until, as the conglomerates which cap the Tertiary section show, the firm-set undecayed rocks were, in certain places at least, exposed to the eroding agents.

The supposition that there was in the Mesozoic period a deep zone of decayed rock in New England which might have afforded, if subjected to rapid erosion, detritus such as is contained in the clays and arkoses of the Tertiary rocks of southeastern Massachusetts, finds some support in the occurrence at many points in that area, particularly in the southern half thereof, of rocks decayed in place under conditions which clearly show that the disintegration has not been brought about since the last Glacial period. Rocks in this state, exhibiting decay to the depth of some score of feet, occur at various points in and about the Boston Basin, and in a number of places in the Berkshire Hills and elsewhere. A notable instance of this decay of the strata in place was found in the excavation of the Hoosac Tunnel, where, for a length of several hundred feet, near the western portal, the mica-schist was found completely softened at a depth of 400 feet below the surface. Owing

to the deep covering of glacial drift which hides so much of the surface of New England, as well as to the fact that the ice of the last ice period removed all projecting rocks of this nature, it is only chance excavations, such as are rarely made, that give one an opportunity to see these remnants of a decay which was once widespread. From a careful examination of the evidence, I am of the opinion that at least one-thirtieth part of the crystalline rocks of Massachusetts, Connecticut, and Rhode Island would, if bared, exhibit decay of the type so well known in the plateau district of the southern Appalachians.

The cause of the sudden removal of this material from its old to its new bed place is not easily determined; the following suggestions seem, however, worth consideration. It is doubtful that the result was brought about by the invasion of the sea during a period of subsidence; the singularly unmixed character of the deposits, the entire absence of marine organic waste, which is likely to be found in beds of this nature, and the perfect assortment into thick layers of like sediments are also against this view. Moreover, the cutting rate of coastal erosion agents is normally slow, while these beds indicate very rapid work of this kind. So, too, the hypothesis of exaggerated land erosion due either to a great increase in rainfall or to a steepening of valleys brought about by a change in the attitude of the land, seems inadmissible for the reason that the detritus from any ordinarily conditioned area would have been stained by the organic waste that all such streams normally bear to the sea. It is difficult to conceive a large river carrying and depositing in succession red and white clays and arkoses without a trace of vegetable detritus.

The difficulty which is encountered in the effort to explain the erosion of the detritus of the Gay Head beds by marine action is well illustrated by what is now taking place on the rapidly wasting cliffs of that part of Marthas Vineyard. The materials of the section are to a certain extent rearranged along the shallow-water belt of the shore, but the various forms of detritus are intermingled, and are mixed with organic matter to such an extent as to make the intervention of the sea unmistakably manifest.

It may be suggested that the beds in question have in some way been bleached or colored since they were deposited. This view can not, as is at once seen, be maintained in the case of the clays, for the lignite beds of the Cretaceous which are mingled with them carry the carbonaceous stain with no trace of bleaching. I have been unable to conceive any chemical action occurring in either the clays or the arkoses which might possibly account for the disappearance of original organic waste.

In this state of the problem I have been forced to bring in the hypothesis that the erosion work which removed the materials of these strata from their parent rocks was effected by glaciation, the ice not attaining to the place of deposition, but delivering the detritus to

streams, one or more of which debouched near this part of the coast into the sea, or perhaps at times into a lake. Glacial action accounts for all the facts which we have noted concerning the character of these deposits in a way that no other operation could well do; in fact, without using this hypothesis we are left quite without an explanation of a very interesting series of phenomena.

In favor of the hypothesis that glacial erosion delivered the detritus of the Cretaceous section to the currents which bore it to its present resting place, we may note the fact that occasionally, though rarely, in the clays of the Gay Head cliffs we find large, subangular masses of a yellowish-red sandstone embedded in the strata. One of these, visible for some years, has recently fallen and broken to fragments. It was originally not less than 20 cubic feet in volume. In the course of the thirty-six years that this slowly retreating cliff has been under my observation, five or six of these interesting fragments have been noted which were certainly not to be classed with the ordinary glacial bowlders that often work down the slopes so as to appear as if they were embedded in the strata. It will be observed that these apparently ice-rafted rocks are of sandstone, a material which sometimes resists the process of decay where all ordinary hypogene rocks yield to it. It is just such a petrographical species as we should expect to find affording the rare bowlder which would be formed where glaciation took effect on an area indicated by much decayed crystalline rocks. Thus in the Connecticut Valley, whence these floated masses possibly came, borne by ice rafts, the sandstones have suffered but little interstitial decay, while the older rocks of the neighboring Berkshire Hills have, as noted, been in places much disintegrated.

The orogenic history of the Cretaceous and Tertiary strata of the New England islands is even more puzzling than are the conditions of their formation. So far, no evidence has been adduced to show the action of mountain-building forces in any of the beds of this age in the region south of New York. To find on this portion of the coast much evidence of dislocation of a high order is surprising; it justifies, indeed, the effort of those geologists who have endeavored to account for these movements by the thrusting of the ice sheet. We have seen that this explanation is for several reasons inadmissible, and the question arises as to the origin of the compressive strains which have acted in this area. To determine this, so far as it is at present determinable, we should begin by noting the following facts:

The amount of the shortening of the beds as shown on Marthas Vineyard, where a cross section having a length of about 5 miles is exposed, is probably nearly 2 miles. This is shown by the fact that the average dip of the beds, as determined by many observations, is about 45 degrees. There is good reason to believe that the area involved in these disturbances is much greater than the exposures on the island seem to indicate. In my opinion the beds may reasonably be supposed

to have at least twice the extension across the strike that is known to exist, and it is not improbable that the area involved may have a width of 30 miles. The dislocations on Nantucket, though not well known, and those noted by Mr. Woodworth on Block Island, and also those on Cape Cod, hereafter to be described, seem in a way to validate this conjecture.

We have next to note that while the strikes of the folds on Marthas Vineyard are somewhat irregular, their commonest direction is from north-northwest to south-southeast, or nearly at right angles to those of the Appalachian folds of the neighboring mainland. This feature at first raised a doubt as to the orogenic nature of these foldings, for the reason that it seemed unlikely that such a departure from the normal strike of the district would take place if the movements were in character like those ordinarily involved in mountain building. But a comparison of the facts with those observed in other areas makes it clear that this discrepancy is not of great significance. In the Cordilleras and elsewhere it is not uncommon to find that the later movements in any mountain system show the effect of stresses acting at high angles, or even normal, to those which were originally effective. It seems, indeed, that the compressive strains of any district tend in the course of time to satisfy themselves through folds running in more than one direction; that when the strains in a certain axis are relieved there is often a tendency to form others in contrasted directions rather than to develop those which were first made. Therefore, the peculiar position of the axes of Tertiary disruption in this area can not be urged as a weighty argument against their true orogenic character.

It is to be observed that the dislocations of the Marthas Vineyard and Cape Cod sections differ in a notable way from those which occur in the older rocks of the Appalachian district. The folds are small, none of them, so far as clearly observed, exceeding a few hundred feet in horizontal amplitude; they are much compressed, and frequently overturned; they are cut by numerous faults, none of which appear to have a throw of more than 100 feet. In some places these accidents of stressing are so numerous and have so intermingled their effects that the result is a confused jumble of entangled beds which can not well be unraveled. At first sight these peculiarities of movements of the Marthas Vineyard section suggest to anyone familiar with ordinary mountain-building work that the strains which have effected them were of a different order from those which uplifted the Alleghenies and other normally folded mountains. It is, however, to be noted that the stresses which acted on these newer rocks took effect under very different conditions from those under which the old strata of the Appalachians were dislocated. There the beds were rigid and deeply buried; here they were soft and had little overburden to oppose their movements when the stress was applied to them.

As yet we have little information concerning the nature of the work

done by orogenic action in the superficial portions of a section on which it has taken effect, but all the considerations derived from laboratory experiments, as well as from the principles of dynamic action, lead us to believe that near the surface of a stressed area the folds are more likely to be small and of varied form than in the deeper-lying parts of it, and that in soft strata without beds of such rigidity as to control the movements slight local accidents are likely to determine the formation of many small folds rather than a few of large size.

It is worth while here to note that these Vineyard dislocations, in case they are accepted as of truly orogenic nature, may well be taken as examples of what is likely to be the type of mountain folding as exhibited in weak beds which, at the time of disturbance, lie within a few hundred feet of the surface. So far as I am aware, there is no better place known in which to study this interesting phase of mountain building.

Assuming, then, that the rocks of the sections exhibited on Marthas Vineyard owe their very great dislocation to forces which had their origin in the under earth, I shall consider certain possibilities as to the exact source of these strains. It may be suggested that a slipping movement has occurred in these beds, due to the formation of a great inclined fault extending parallel to the shore and dipping toward the sea at a high angle, the resulting movement being in effect a landslide. This view is inadmissible for the reasons that there is no trace of such a slip fault; that the section moved is of a rank in size of which we have no knowledge elsewhere; that the transverse shortening of the beds is too great to be accounted for in this manner, and that the direction of the axes of the folds is at about right angles to such as would be formed in such a movement.

It may be worth while to set forth another hypothesis which I have been led to apply to these movements in order to arrive at an explanation of them without recourse to true mountain-building action. This is as follows: A large part of the materials in the Marthas Vineyard section is feldspar, which had apparently been imperfectly kaolinized before it was brought to its present site. Is it not possible that the considerable increase of bulk attendant on this conversion of feldspathic matter into kaolin may have led to internal pressures? It appears, however, that of the mass not over 15 per cent can be reckoned as feldspathic, while even if the whole of it were of that nature and all the changes had come about since the beds were laid down the amount of enlargement would be too small to account for the observed disruption of the beds.

It seems evident that we must account for the folding and other movements of the Tertiary and Cretaceous rocks of these New England islands by the ordinary process of mountain building. Questions then arise concerning the nature of the dislocations by which the compressive strains were applied to these superficial beds. The general slope of the hypogene and Carboniferous rocks on the neighboring

mainland makes it eminently probable that these old deposits underlie the newer beds at a depth of not more than 1,000 or 2,000 feet below the surface of the sea. How, then, were these lower beds affected in order that they might transmit the strain to the Mesozoic and Cenozoic deposits? and what, if any, were the dislocations on the mainland that were produced at the same time? It seems to me that neither of these questions is, in the present state of the inquiry, answerable with any measure of affirmation, but some suggestions may be made which are perhaps not without value.

As to the movements of the rocks, presumably crystalline, that constitute the foundation of the Marthas Vineyard section, the conditions are substantially the same as those which have existed beneath the Carboniferous deposits of the Narragansett Basin. When they came to be folded, with a measure of compression quite like that which has affected the beds with which we are now concerned, as we may see when the folded Carboniferous beds have been stripped away from the hypogene rocks, the yielding of the crystallines appears to have been made mainly by the interstitial movements of those rocks, and not to any great extent by faulting. All the evidence we have goes to show that while ordinarily massive crystalline rocks may be folded, as is sometimes indicated by the dikes they contain, a frequent method of accommodating themselves to pressure is by squeezing. This action is, indeed, common enough in all rocks which have been subjected to compression strains, as is shown in the distortion of fossils. The absence of any distinct indication of recent faulting on the mainland near Marthas Vineyard affords some support to the supposition that the giving way of these basement rocks was rather more by interstitial movement than by dislocation.

It should also be said that the peculiar position of the masses of decayed crystalline rocks which, as above noted, occur in the three more southern States of New England, long ago led me to the supposition that, after this decay had been effected, a certain amount of faulting occurred, which lowered wedges of the disintegrated rock down to levels to which the surface actions had not penetrated. Moreover, efforts which I have made to account for the details of the topography at several points in southern New England have led me, quite independent of the problems of the Tertiary dislocations, to the idea that at a time not long before the last Glacial epoch there was a certain amount of disruption by faulting in that part of the mainland. This problem of recent faulting on the mainland needs more study than I have been able to give to it; the matter is only suggested here to show that there may be more extensive evidence of orogenic action on this part of the continent than has hitherto been supposed.

A part of the difficulty connected with the question as to the nature of the movements involved in the dislocation of the Marthas Vineyard section arises from the fact that the development of these folds and

faults has apparently taken place in a basin without a border of harder rocks on either side through which the compression strains might have been carried. It seems likely that the contraction of the basement beds, however great, would have failed effectively to compress a thick mantle of soft material unless it had been in a basin. The natural result, if the beds lay on a sloping floor without a rim, would appear to be a mere slipping of the bed rocks upon the softer materials, without any such folding as we find. There are obviously no marks of a basin structure made up of the older rocks in the district where these disturbed beds lie. It is possible, however, though there is no evidence whatever to support the suggestion, that there may be a rim of such older rocks lying below the level of the sea.

There is, as is generally admitted, good reason to believe that this portion of the continent stood, in the period extending from the close of the Trias to the beginning of the Cretaceous, at a much higher level than it does at present. During that time a broad river basin may have been excavated in which the Marthas Vineyard Cretaceous and Tertiary were laid down. I have elsewhere called attention to the fact that the Carboniferous beds of the Narragansett district and other local accumulations along the Atlantic coast appear to have been formed in drowned river valleys, and that the beds have since been subjected to mountain-building actions, the trends of the resulting folds having often departed widely from the trend of the neighboring axis of the Appalachian system. I am disposed to think that the Tertiary and Cretaceous beds of Marthas Vineyard have had the same general history, but the fact must be recognized that the evidence to support the conclusion is defective. All that can be said in its favor is that it is consistent with the basin-like origin and structure and the nature of the folding which characterize the localized mountain-built areas of the Atlantic coast.

We now come to the subject of the erosion phenomena of this district, and here we find ourselves in an interesting but difficult field. Beginning with the island of Marthas Vineyard—Capawok, as the Indian name has it—a district which gives us the most information concerning the structure and history of the field, we find there good evidence that the Tertiary and Cretaceous rocks have been subjected to a great amount of erosion since they were dislocated. On the western half of that island these beds rise to a height of about 300 feet above the present level of the sea. As there is an area of about 30 square miles where the crests of the divides have about the same elevation, there is good reason to believe that the existing topography was carved from a surface which, by base-leveling, or more likely by marine erosion, had been brought to an approximate level before the last Glacial period. If I am correct in supposing that there had been a tolerably complete base-leveling or benching with reference to a sea level above the tops of the present divides, then the development of the

present topography began long after the close of the mountain-building work.

The pre-Glacial topography of Marthas Vineyard has been but little disturbed either by glacial erosion or by the resulting drift coating. We can see that the course of the principal brooks—rivers, as they are locally termed—has been determined in general by the strikes of the beds coinciding therewith, while the smaller water courses cut across the folds in a normal way. The beds being all of slight hardness, the topography is smooth, but here we find sharp and continuous ridges which owe their relief altogether to differential erosion. These serve to show us how slight has been the wearing effected by the glaciers of the last ice epoch. The absence of such ridges on the remnants of the ancient upland plain also indicates that this plain was due to some action which wore it to a tolerably perfect level.

So well has the pre-Glacial topography of this island been preserved through the accidents of glacial invasion, that we can not only trace two or three cases of ancient stream robbery, but a close inspection makes it evident that all of the brooks of considerable size follow at the present time the channels they had before the ice came. In only two cases have I found that the morainal or other accumulations have changed in an important way the course of the waters. I note these points in order to show that the evidence from these streams as to the general drainage of the district is of value.

Taking the distribution of the brooks of Marthas Vineyard, we note that they are divisible into two groups—those which, turning south, fall into the broad ocean, and those which, descending from the northern side of the island, enter Vineyard Sound. The first-named group of brooks gives us little information except that they enter the sea through what appear to be drowned valleys, and are therefore evidence that the level of this land has been materially lowered since the existing topography was formed. The streams of the northern shore exhibit even more distinctly the same feature of drowning at the mouths, though this is marked, not by their entrance into lagoons, but by the filling of their channels near the sea level by moving sands. On this northern shore also we find in the distribution of the brooks the suggestion that when the land was at the level at which the river topography of the district was developed they entered a large stream occupying the central part of the broad valley now covered by Vineyard Sound.

The general structure of Vineyard Sound is easily misconceived. It has been suggested by Mr. Clarence King that the long range of the Elizabeth Islands, which form the northwestern boundary of this water body, is essentially morainal. There is undoubtedly a covering of morainal drift on the top of these islands, but on examination they prove to be composed mainly of beds similar to if not contemporaneous with the Nashaquitsa section. They probably contain also some part

of the Gay Head Tertiary beds. There are no good exposures, but enough is shown to make it clear that the Tertiary portion of that section is above the level of the sea along this line of islands. This condition of a sheet of moraine capping a divide is seen also on Marthas Vineyard, where the broader valleys are in their lower parts almost

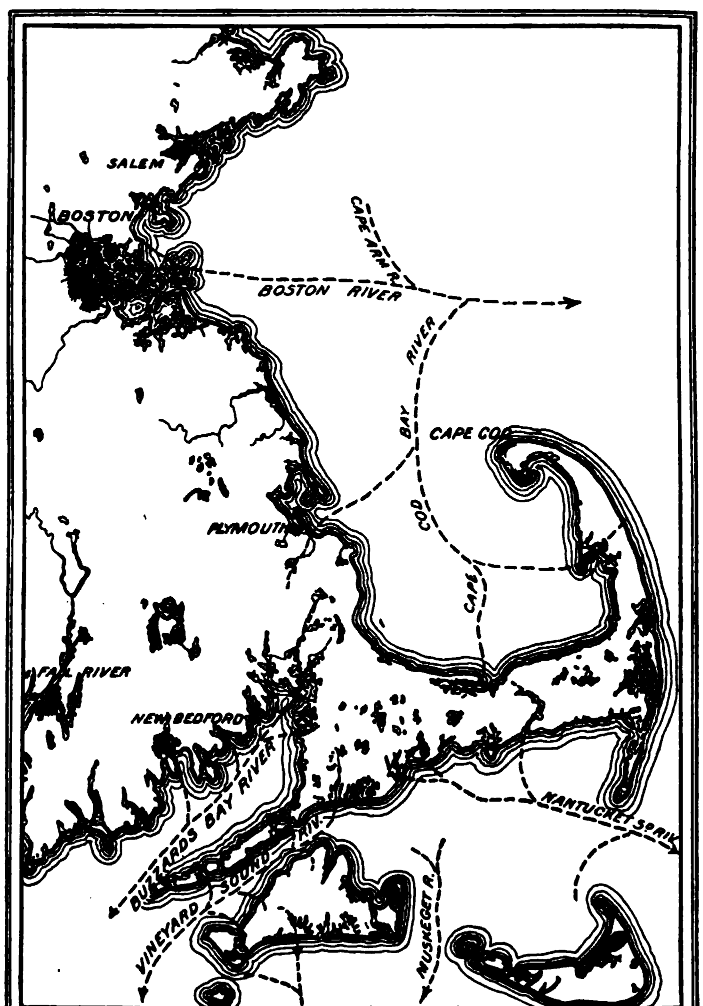


FIG. 86.—Sketch map showing the probable position of the streams of the Cape Cod district during the period of elevation preceding the last Glacial epoch.

driftless, while the crests of the ridges are usually crowned by a layer of morainal materials having a depth of from a few feet up to about a hundred feet. This feature goes to show that deposits of this nature tended to accumulate on the high ground. We shall have occasion to examine this matter more closely when we are considering the distribution of the moraines in the Cape Cod peninsula.

The fact that the Elizabeth Islands are not essentially morainal greatly increases the probability that the valley of Vineyard Sound was excavated by river action. The stream which occupied it during the period of elevation, when the erosive work was done, appears to have had its source on the southern side of Cape Cod. On the west of the Elizabeth divide, in the valley of Buzzards Bay, there was, if this conception of the history of the district be correct, another river which headed in the region about Wareham, taking about half its drainage from the district underlain by the ancient rocks of the mainland. In both these valleys we find the general features of drowned valleys exhibited quite as they are shown in the more southern bays of the Atlantic coast. The basins slope to the seaward, but not in a perfectly regular manner, for the reason that they are much encumbered by drift accumulations and by the waste that has been rearranged by the strong tidal currents which sweep through the bays and sounds of this district. They both widen to the seaward, as we should expect them to do if they had been excavated by the action of land waters.

The position of a third stream is perhaps traceable on the Muskeget Channel, which separates Marthas Vineyard from Nantucket. This headed against Cape Cod and against the upper tributaries of the Vineyard River, as we may call the stream which occupied the sound of that name. It is likely that to the inosculation of these headwaters we owe the formation of the channel which now separates the islands last mentioned from the peninsula of Cape Cod. In the sketch, fig. 86, the conception of the drainage of this district as it was before the last great upward movement of the sea is indicated. In such a figure it is inevitable that many features which are highly conjectural should be shown along with those which are well supported by evidence. In this case the doubt which is the most serious attaches to all that relates to the channels between the eastern end of Marthas Vineyard and the western side of Nantucket and between the last-named island and the mainland. As the tidal currents which flow through this water way are strong, some part of the erosion may have occurred both before and after the last Glacial period, at those stages of elevation and subsidence when the sea was free to pass through these channels. There is also a question as to the nature of the submarine ridges which so abound in these waters.

As regards the shoals of Vineyard and Nantucket sounds, it may be said that some of them, particularly those in the eastern portion of the last-named sound, are of moving sands, and, therefore, may have no relation to the continental topography. Some of these submerged ridges are more reasonably to be considered as preexisting, though their shapes may have been modified by tidal currents. Thus the long shoal, known as the "Middle Ground," which extends along the north shore of Marthas Vineyard from near the west chop of Holmes Hole halfway or more toward Gay Head is, as we may judge from the sound-

ings, a bit of submerged land topography. Although it is now the line of a strong division of tidal currents, and is consequently the seat of a "rip," this perturbation in the movement of the water appears most likely to be the consequence and not the cause of the elevation. So, too, in the case of the shoals to the northward and eastward as far as near Monomoy, there is nothing in the tidal movements which are competent to produce them, though the resistance which they offer to the movement of the currents has doubtless served to effect changes in their forms. If the statements of those fishermen and pilots who know these waters well may be trusted, these submerged ridges often contain on their surface considerable bowlders, which, if true, indicates that they are not in most cases the products of current action, but were formed mainly by subaerial agents of erosion.

It is to be noted that the channels south of Cape Cod to the west of Monomoy Point have in general a definite topography, characterized by steep slopes from the neighboring shores. This form of bottom seems to me inconsistent with the supposition that any great amount of sand is in the possession of the currents along these depressions. It is also noticeable that there is little trace of shifting sands along the shores on either side of Vineyard Sound. Furthermore, it is to be remarked that these valleys, as is shown by the protraction seaward of their very definite land slopes, have not been cut back on the average more than from 500 to 1,000 feet since the shore came to occupy its present level. All these considerations lead me to believe that the floor of these basins is not occupied to any great extent by drifting sands. For the reasons given above, the shoals to the east of Monomoy have been in general regarded as evidence of minor divides formed in the great submerged valleys.

The oscillations of sea level in this region have been more than once referred to in the preceding pages of this report. We have now to review the evidence, with a view to formulating it in a definite manner. It should be noted that there is in this district little, if anything, in the way of ancient beaches to afford data as to the altitude of the land in the periods which are under consideration.

On the mainland to the northwest of this region there are evidences of a base-level of river erosion or of marine planation, which Professor Davis and others regard as of Cretaceous age. The portion of this level at about 400 feet above the present shore line possibly corresponds with the present summit of the Cretaceous deposits of this island nearly enough to warrant the supposition that the sea stood at a height of some 400 to 600 feet above its present position when the lower Cretaceous of Marthas Vineyard was laid down. It should, however, be noted that those beds, owing to their dislocation by mountain-building action, may have been moved either above or below the general plane on which they were deposited.

It is evident that the lignitic portion of the Cretaceous beds was

laid down rather above than below the sea level, while the deposits containing marine fossils were formed below the plane of the sea. There is thus evidence of shore swaying in this portion of the section. As yet it has not been clearly determined which of these two elements of the Cretaceous lies the higher. The facts show, however, that in this part of the formation the shore was near its present level, and that it was instable.

Between the lower Cretaceous and the middle Tertiary there is a great blank, which includes the uppermost Cretaceous and the Eocene. As yet, the much-disturbed condition of all the beds showing the contacts of those horizons makes it impossible to say what measure of unconformity existed between them when they were laid down. It seems probable, however, that no mountain-building action had taken place in the district during this interval.

It is not yet perfectly certain that the middle Tertiary strata of this district were deposited in salt water. The marine fossils contained in the beds are found under conditions that admit of the supposition that they were not living when the strata were formed, but were swept in from previously existing deposits. I am forced to regard the determination of the age of this section as in some measure uncertain, but it is clear that it is newer than the Eocene and older than the Pleistocene. The general nature of the beds is most consistent with the supposition that they were formed in an estuary. Assuming that they were made at or about sea level, we should have to conclude that there had been no great change in the position of the shore line between the lower Cretaceous and the Miocene periods, or, what is more likely, that there had been a return of the seashore to about its same altitude in relation to the land after whatever oscillations it had undergone in this long interval.

In the Pliocene, as is shown by the fossils contained in the small locality, now destroyed, at the top of the Gay Head cliff, it is evident that, for a time at least, a shallow sea lay over the surface of the Tertiary beds, which were still in their horizontal position, for these Pliocene beds were evidently involved in the mountain-building movements. It can not be inferred that the altitude of these fossil-bearing Pliocene beds above the sea (about 100 feet) is evidence of a general upward movement of the shore, for the reason that the change of level may have been due to the folding of the strata.

The deposits of the Nashaquitsa series apparently indicate the existence of the shore line at least 100 feet below its present altitude. These beds may be regarded as closing the Pliocene record, and as formed, in part at least, before the orogenic movements took place.

After the series of constructive processes above noted had been accomplished, the beds of this district appear to have been established at a level some 200 or 300 feet lower in relation to the sea level than their present position. During the time in which they occupied this inferior level the upper base-level or bench of Marthas Vineyard prob-

ably was formed. It may, in passing, be remarked that the general topography of the bottom of the sea, from the southern end of Nantucket Shoals to Nova Scotia, is in favor of the supposition that we have in this district a surface that preserves in a general way the contours impressed upon it by subaerial erosion.

The down-sinking of this region some time during the Glacial period probably brought about the drowning of the great valleys. It evidently resulted in a lowering of the land at least 100 feet below its present altitude, as is shown by the fact that the morainal aprons or sand plains which are so conspicuous a feature in Marthas Vineyard, Nantucket, and Cape Cod attain about that altitude. These aprons are, as elsewhere noted, composed of sand and gravel, with occasional bowlders of considerable size, which evidently attained their present sites by ice rafting. They have, however, a characteristic submarine topography, such as could not well have been made by any form of subaerial action. The "scour ways" noted in the report on Marthas Vineyard[1] as existing on these aprons are of themselves sufficient to establish the presence of the sea over these plains.

As yet there is no evidence concerning the upper limit of this submergence, which occurred in and possibly before Glacial time. After a careful search throughout southeastern New England, the shore line of the sea in the time when the morainal aprons were formed has not been found. Here and there, at the height of about 200 feet, there are what may be faint traces of a coastal shelf, but they are too indefinite to afford any clear evidence of such a line. The distribution of the drift in the southern part of Marthas Vineyard, in the towns of North Tisbury and Chilmark, is such as to suggest that the glacier did not, save in certain small tongue-like projections, extend south of Tisbury River, and that the drift south of that stream was all rafted to its present site. If this view be confirmed by closer study of the deposits, it will affirm the hypothesis that the whole of the island was under water, for the materials which appear to have been thus transported are found on the very highest land, at an elevation of 300 feet above the sea.

I have elsewhere[2] endeavored to show that on the southern face of the hills of Mount Desert, Maine, we have good evidence of a depression at the close of the Glacial epoch amounting to at least 1,100 feet, and possibly extending up to the highest summits, or 1,527 feet. It seems likely that a depression of even the lower of those levels on the coast of Maine would have involved a submergence in the region of Cape Cod sufficient to have covered the highest lands in that vicinity. It thus appears probable that the Glacial submergence of this district carried the whole of its area below the level of the sea.

The emergence of the Cape Cod district from the Glacial depression must have been very rapid, for the surface appears substantially as it

[1] See Seventh Ann. Rept. U. S. Geol. Survey, 1885–86, p. 316.
[2] See Eighth Ann. Rept. U. S. Geol. Survey, 1886–87, p. 1009 et seq.

was left by the ice. The delicately molded topography of the drift has not been effaced by wave action, nor, as before remarked, are there any traces of ancient beaches. At first sight this absence of any effect of the waves on the surface seemed to me clear evidence that the area could not have been under water since the disappearance of the glacier. In order to determine this point, I visited the region below the elevated beaches in central New York, and found there the same unaffected conditions of surface which exist in southeastern Massachusetts. The conditions of submergence and emergence must have been approximately the same in both areas. It appears, therefore, that we have to accept the conclusion that the uprising of the land after the Glacial period was so sudden that the waves and shore currents did not have time to do effective work. It is possible, however, that the waters were at this time so far obstructed by floating ice that no great amount of wave action took place during a considerable length of time in which the elevation was going on. The last change of level of the Cape Cod district evidently brought the land somewhat above the plane at which it at present stands. This is shown by the occurrence at various points of submerged forests, as in Nantucket,[1] and in the marshes bordering the harbor of Holmes Hole, Marthas Vineyard. The amount of this recent downward motion is not known, but it may have been sufficient to obliterate the land connection which united the islands of Marthas Vineyard and Nantucket with the mainland. The reason for supposing a connection between these islands and the mainland is found in the substantial identity of their faunas and floras with those which exist on the neighboring continent. Considering the width and current-swept nature of the sounds which separate those islands from the mainland, it appears unreasonable to suppose that all these species of animals and plants could have found their way to the outlying stations in the short time which has elapsed since the Glacial period. The conditions of passage are almost as difficult as they are at the straits between the islands of Bali and Lombok, which separate the biological provinces of Australia and southern Asia. As there has been a subsidence since the forests regained possession of these islands, it is reasonable to suppose that the previous elevation was great enough to bring about a connection with the mainland.

It is to be noted that the changes in the relative elevation of sea and land have all been spoken of as if they were due to changes in the altitude of the land. It should be observed that this assumption is incorrect. There are at least two main and efficient causes of alteration in the position of the sea in relation to the land, as well as many others of minor importance which probably have some value. One of these, local in its nature, is the swaying of the land against which the sea lies; the other is change in the form of the sea bottom affecting the height of the open waters along all the shore. It is rarely possible to differentiate these causes. In the case of the Iroquois beaches in central New

[1] See Bull. U. S. Geol. Survey No. 53, p. 28.

York, the fact that they rise to the north supplies a criterion, the like of which may be found in other places, which indicates that the post-Glacial elevation was due to a land movement. Again, as I have elsewhere endeavored to show,[1] the very general drowning of the lower valleys of the rivers of all the continents affords evidence that there has been, in very modern times, a general rise of the sea level to the amount of 100 feet or more. It is to this general inundation that we may perhaps attribute the destruction of the land bridge which for a long time after the close of the Glacial period united the New England islands with the mainland.

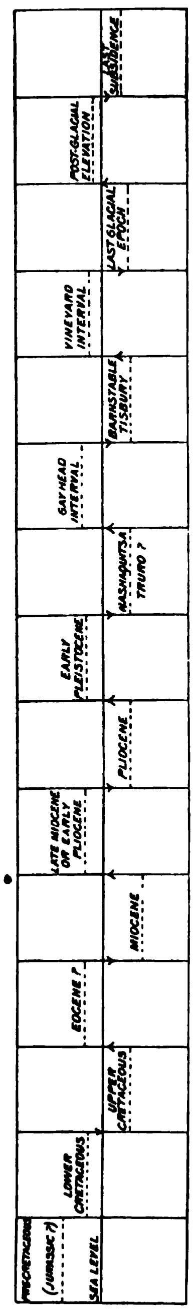


FIG. 87.—Diagram showing the probable movements of the Cape Cod district since the Jurassic period.

There is some evidence as to the duration of this land bridge to be derived from the possible rate of marching of the oaks and other heavy-seeded trees northward from their southern refuge during the last ice time. These trees, in the process of repossessing an abandoned field, do not, according to my observations, advance at an average rate of more than 5 feet a year. To assume a rate of 10 feet a year would be to allow the utmost that could be supposed. This would require about 500 years for a mile of journey, or about 2,000 years for the passage across a land bridge from the mainland to the island of Marthas Vineyard. I have elsewhere urged this slow rate of northward march of the heavy-seeded trees as an argument against the hypothesis that the close of the glacial advance, when the ice lay at the southernmost point it had attained, was not more than from 10,000 to 20,000 years ago. If the argument be valid, the return of the oaks to southern New England, after their expulsion to regions farther south, must have required somewhere near 200,000 years.

It is possible that some of the topographic features of the submerged channels of this area are due to the erosion which took place during the elevation that followed the Glacial period. The cutting away of the divide between what we have supposed to be the drainage basins of the Vineyard and the Muskeget rivers may have been in part effected by the energy of the tidal currents, which, in case the passage were diminished in sectional area, would act with something of the strength they now have in passing from Vineyard Sound to Buzzards Bay through the shallow passage known as Woods Hole.

[1] See Bull. Geol. Soc. Am., 1895, p. 153 et seq.

We have next to consider the erosion performed in this district by the ice of the Glacial epoch. It is now well known that the original conceptions as to the amount of this wearing on the general surface of the country were very much exaggerated. There are few students of the phenomena in the field who would be disposed to believe that the average of this erosion in New England amounted to as much as 100 feet. I doubt whether it was as much as 50 feet. It has commonly been supposed, however, that in incoherent materials the action was more effective than in firm-set, highly changed rocks. So far as we can judge from the conditions seen on Marthas Vineyard, where the contact of the drift with the underlying sands and clays is well revealed by the cliff sections and the clay pits, the glacier did little more than smooth over the soft materials without effacing their original outlines. In no case is any considerable amount of the characteristically colored clays and sands mingled with the till covering. It is usually impossible to find a trace of them at a height of 2 feet above bed rock. When we consider that this occurs at points where the ice has journeyed for a mile or more over the soft beds the absence of all marks of erosion is seen to be very remarkable.

I have already noted the fact that the glacier failed to destroy even the minor features of the topography of this field. It is difficult to exaggerate the extent to which the pre-Glacial topography survives in the Vineyard area. The facts must indeed be seen, and this carefully, to be appreciated. There is one way, however, in which the glacial conditions effected a considerable amount of local erosion in this district. This was by the action of the subglacial streams which flowed upon the surface of the bed rocks. All along the northern face of Marthas Vineyard we may trace these subglacial river ways, which extend from the shore in winding, sometimes beautifully curved, channels cut down into the soft rocks to where they discharged beyond the front of the ice. Sometimes these channels are coincident with earlier-formed valleys. Again they are carved where it is evident that open-air streams have never flowed. The largest, and in some ways the best, example of these interesting and elsewhere unnoted features is seen at Chappaquonset or Tashmu Pond and in the valley which continues the depression to the southward. As elsewhere noted, these grooves, extending from the shores of Vineyard Sound upward, terminate on the south in the morainal apron, or, rather, are continued over that apron in other shallower and wider troughs cut in the sands which extend downward to the ocean shore. In some cases the bottoms of the grooves which were under the ice have been worn down to the depth of 60 feet or more into the soft bed rocks.

It is likely that the low places in the Elizabeth Islands divide, as at Woods Hole, Quicks Hole, and Robinsons Hole, as well as certain others which do not go below the level of the sea, are due to a like action of subglacial streams when they crossed the ridge lying between

the sound and the bay. Similar valleys will be noted in the detailed account of the structure and topography of Cape Cod.

We have last to consider the extent of the post-Glacial marine erosion which has occurred in this district. This has been and is still great; at present it is some hundredfold greater than that done by land waters, but the distribution has been in certain regards peculiar. As before noted, the marine benching of this district which occurred after the deposition of the Pliocene strata was apparently pushed to the point where the whole area of the Cretaceous and Tertiary rocks was brought to a level. This may possibly have been due to base-leveling by stream action, but whoever will observe the practical absence of such work on the strong topography of Marthas Vineyard, where the brooks are never colored by the soil waste and where there is not a single stream scar, will hesitate to hypothesize this slow process of lowering to a common level such rocks as here occur. There are on Marthas Vineyard pretty clear evidences of the existence of a second level of marine benching at the height of about 150 feet above the sea. This bench is recognizable around nearly the whole of the western elevated section of the island, and as there is no structural basis for it it must be regarded as of marine origin. Its original width can not now be determined with accuracy, for it is much diminished by marine erosion, but on the average it can not well have been less than one-third of a mile, and may have been more than twice as great as that amount. Thus the pre-Glacial erosion due to the sea apparently includes two large operations, the formation of the original level surface of the island and the cutting of the lower bench, which was a much less extensive work. As to the benching which may have been done in the sections below the water level, the evidence, though in a way interesting, is too perplexing to warrant discussion.

The post-Glacial marine erosion of this district has been extensive and is now in process of very rapid development; no other portion of the coast of North America is undergoing such a complicated and rapid readjustment. When the problems which are there presented concerning the action of the sea on the shore and the arrangement of the detritus derived from the process of erosion are worked out, this area will become the classic ground for students of coastal action. For our purpose it will be well to divide the question into two heads, the first relating to the amount of erosion already done, the second concerning the manner in which the work is effected.

In this, as in most other shore lands, the only possible way of determining the extent to which the sea has gained on the land is to take the slopes which extend downward to the sea and ascertain where, if protracted, they would cut the water level. This method is particularly applicable on shores such as those of southeastern New England, where there is a gentle slope toward the sea. On this basis, using for data observations made at some scores of points, I have come

to the conclusion that if the land had been stable since the last ice time the average retreat of the shores might safely be estimated at rather more than about one-half a mile. Unfortunately for the sufficiency of this method, it is certain that there has been a subsidence, which may be, and most likely is, now going on, so that the resulting work of the sea is not the formation of a horizontal shelf but of a sloping scarf, much of which is submerged. Thus we can only say that, the rate of the down-sinking being unknown, we are deprived of any means of accurately fixing the extent of the incutting since Glacial time, and are driven to the ruder method of noting the amount of recession of particular cliffs.

Turning to the evidence afforded by the cliffs, the best obtained is that due to the surveys of the late Prof. H. L. Whiting, long the senior assistant of the United States Coast and Geodetic Survey, who fixed the rate of erosion of the Nashaquitsa cliffs by very careful observation for a period of fifty years at 3 feet per annum.[1] The evidence is clear that this is the rate for nearly if not quite the whole southern shore of Marthas Vineyard. At Gay Head there are only approximate data, which serve to show that most likely the retreat does not amount to as much as a foot per annum. Along the north shore of Marthas Vineyard the process of erosion is very slow, save at a few salient points west of the steamboat landing. At West Chop the rate does not average a foot in five years, but at the east and west chops of Holmes Hole the cliffs have for some years been retreating at an average rate of at least 2 feet per annum. This wearing is probably in some way connected with slight alterations of the shoals which direct the tidal currents against the shore. On the Cottage City or eastern face of the island the rate of wasting is also great. The recession of the shore has amounted to at least 30 feet in fifteen years, and this despite some slight efforts made to resist the action of the waves. The region near Edgartown is amply protected on its east side by the extensive system of hooks about Cape Pogue. As a whole the shores of Marthas Vineyard in process of erosion, excluding the island of Chappaquiddick and the Cape Pogue hooks, are probably entering the land at an average rate of about a foot a year. The mean height of the sea-cliff face may safely be taken at 30 feet, and the total face subjected to erosion at 35 miles. This would make the quantity of material removed amount to a total of about 1,000,000 cubic feet per annum.

On the island of Nantucket, owing to the extent of the sand-barrier beaches, the proportion of the total shore line which is exposed to active erosion is less than that of Marthas Vineyard, but the wearing action of the sea is much more effective, for the reason that clays rarely appear in the escarpments, which are mostly of stratified drift, such as is found in the morainal aprons. The southern shore of the island and a portion of its northeastern face are apparently retreating at the rate of

[1] Geology of Marthas Vineyard: Seventh Ann. Rept. U. S. Geol. Survey, 1888, p. 361.

more than 4 feet per annum. Yet, for the reason above given, it seems likely that the average encroachment of the sea is much less rapid than it is in the island of Marthas Vineyard.

The Elizabeth Islands are wasting for the greater part of their length, but the process is now being arrested by a simple action which has brought protection to much of the shore lands of southeastern Massachusetts. The mass of these islands is, as before noted, of incoherent sand, but the surface is generally occupied by a layer of coarse till or moraine, having a depth of a few feet. As this pebbly and bowldery matter falls to the shore it forms a stony beach. This plating over the soft underlying beds is sufficient to prevent the shore currents from wearing them away. The result is that a platform is made on which the waves break before attaining the shore, and often a barrier beach is formed which to a great extent keeps even the swash from attaining the cliffs. When the adjustment has gone thus far, the shores erode only so fast as is necessary to supply the place of the pebbles which are worn out or the larger waste brought about by the action of the shore ice in rafting away the stones, as it does in a very effective way. An excellent example of the value of these conditions in hindering marine erosion is shown at Gay Head, where, despite the ease with which the strata slip downward into the sea, the vigor of the assault of the waves, and the complete and rapid removal of the sands, the retreat of the escarpment is slower than that of many other less exposed shores on this part of the Atlantic coast line. The bowldery drift, though not large in amount, is enough to have formed a shelf extending irregularly out from the face of the cliffs to the distance of nearly a mile. On this the heavier seas break, so that when running from their prevailing direction only the secondary waves attain the shore, with so little effect that the retreat of the face is at the present time less than a foot per annum and appears to be rapidly diminishing in its rate. On the other hand, the Nashaquitsa cliffs, which in their retreat contribute but little bowldery material to the sea, are, as above noted, retreating at the rate of 3 feet a year, the sea having no difficulty in deepening the bottom as it works in, so that its waves are able to assault the base of the cliffs.

On the peninsula of Cape Cod we find evidence of marine erosion essentially like that on the islands which lie to the southward. The details of this action will be noted in the section of this report which is devoted to the topography of that area, but the general features may well be considered here. The most interesting point is that probably all of the invasion of the sea occurs on the southern and eastern (or outer) part of the peninsula, there being little trace of it on the northern (or inner) shore. This is in part for the reason that the seas strike in times of heavy storm with greater effect in this portion of the coast, but in larger measure it is owing to the fact that strong tidal and shore currents sweep by this part of the coast, which carry away the

débris delivered to the sea by many of the cliffs, so that it does not encumber and protect the shores.

On the northern shore of Cape Cod the surface has, as will hereafter be noted, a long riding slope of the glacier, composed usually of clay, which descends gradually to the sea level. This slope extends from the western border of the town of Barnstable to Yarmouth and is partly indicated as far as the town of Brewster. Where this gentle declivity passes beneath the sea, or where it attains the fit depth of water, a beach is formed which incloses the great marine marshes that are so prominent a feature of this part of the coast. This beach is slowly working inland, but the amount of sand which accumulates in the bay it faces is so great that the excavation of the bottom necessary to the inward march of the beach hinders the movement.

On the north shore of Cape Cod the distribution of the products of coastal erosion indicates the weak action of marine currents. On the south side, in the waters between Hedge Fence Shoal and the open sea to the eastward, the distribution of the shoals and spits shows a considerable amount of movable débris in the possession of the sea and its conveyance by strong currents. In the field about Monomoy the struggle between the accumulating sands and the currents is so active that there is evident danger of the passage to the seaward between Nantucket and the cape being closed before many decades have elapsed. If in any time of great storm this channel should become so shallowed that the waves would break across it, the result would be the immediate construction of a barrier beach. If this construction failed to attain to or near the surface, it would doubtless be swept away by the tidal currents. If, however, it made an effective barrier to their flow the island of Nantucket would be again joined to the mainland. An accident of this nature is possible; it is likely, indeed, to be the next great change in the conditions of this part of the Atlantic coast.

As before remarked, the unstable sands of the bays on the eastern side of Cape Cod appear to be mainly limited to the eastern portion of these waters. In Vineyard Sound the evidence from the shores and soundings indicates that the amount of sand at the disposition of the currents and waves is not large. The shores are generally pebbly and the soundings are not to any extent variable. The harbors, such as Tarpaulin Cove, Woods Hole, Holmes Hole, and Edgartown, though so placed that they would naturally be obstructed by moving sands were large quantities of such materials in unstable positions, show little tendency to fill in. The sand beaches, such as those at Menemsha light and between Sengekontacket Pond and the sea, are evidently not gaining in width. These conditions are in very distinct contrast to those which are found in and about Nantucket Sound and Muskeget Channel, where there is a ceaseless oscillation of the shoals and where the harbors which exist are in constant process of closure, against which, as at Nantucket, the precautions of the engineer seem to be of little avail.

The reason for this difference is not perfectly clear; it is probable that it is in part due to the relatively large amount of waste contributed to the sea by the degradation of the shores of Nantucket and Cape Cod, but in a measure also to the fact that the average run of the tides seems to bear the sands to the eastward to a point where the energy of the Atlantic surges, rolling in from the eastward, tends to beat them back into Nantucket Sound.

It seems likely that something like this peculiar condition which we now find in the shoals of the Monomoy group existed a short time ago in the region of Nantucket Shoals, although as yet we do not know enough of these shallows accurately to determine their history. It is probable that it represents the remains of a system of low islands, shoals, and tidal channels which were depressed beneath the sea at the last subsidence. If we should conceive the shore to be 50 feet higher than it is at present, the struggle of the tides and other currents which now exists about Monomoy would be transferred to the region of Nantucket Shoals.

UNDERSTRUCTURE OF CAPE COD.

On first inspection the body of Cape Cod, i. e., that part of it which lies between Monument River on the west and the sand spit which sets in just east of Highland light, appears to be made of glacial débris. It is true that nearly the whole surface is covered either by the extensive moraines which are to be described in the next section of this report or by the deposits of sand and gravel which are spread on the south and east of the morainal accumulations. These superficial accumulations are so extensive that they very effectively mask the true character of the underlying deposits. None of the streams form sections which reveal the underlying beds, and the only cliff shores which do this are near Highland light, where the evidence, as will hereafter be noted, is not very indicative. I therefore deem it necessary to give in some detail the evidence which goes to prove that there are large areas of relatively old strata lying beneath the glacial beds of this district and above the level of the sea.

Beginning with the southwestermost portion of the cape district, that which is in the town of Falmouth, we observe in the fields about Quamquisset Harbor a quality of surface which clearly indicates the existence of deposits other than those of glacial origin. The topography is evidently older than the last ice time, the valleys being somewhat encumbered with deposits of drift. Sections through the ridges show beneath the thin detrital coating a series of somewhat indurated sands, gravels, and clays, usually thin-bedded, though some of the clay layers are 2 feet or more in thickness. The sands and gravels are rather ferruginous, and sometimes the iron oxide is sufficient in amount to produce a distinct cementation. The clay beds range in color from whitish, through brown, to distinct reds. The materials and their

association are essentially like those belonging to the Nashaquitsa series, as shown on Marthas Vineyard. The pebbly matter is rarely of crystalline rocks; it consists almost altogether of quartz and quartzite. In the places where shown in rather small openings it seemed likely that the few pebbles of a granitic nature had been brought to the ground by the glacier and crushed into the mass by ice action.

The most notable feature in the "Quisset" Harbor section is the considerable dislocation to which the beds have been subjected. The layers are thrown into short, abrupt folds, the resulting dips being at several points as much as 30 degrees of declivity. The strikes are irregular, but, as on much of Marthas Vineyard, incline to a general northwest-southeast direction. The condition of the folded beds, especially the fact that a topography somewhat obstructed by glacial deposits but otherwise undisturbed was carved on them in pre-Glacial time, clearly indicates that here, as on the island last named, the disturbances can not be accounted for by the movement of the ice. The important exposures which have yielded this evidence were made in 1896 by a land company in grading the roads of its property. They are, unfortunately, of a nature to be soon effaced.

The topography and the distribution of the "spring levels" (or places where the water contained in the drift is turned to the surface by the clays) of the region about Woods Hole indicate that this Nashaquitsa series—for such we shall term it—rises to the prevailing height of about 60 feet above the sea, being capped by the ridge of the moraine which runs parallel with the shore of Buzzards Bay. Northward along the shore of that bay the conditions of surface, as explained by the above-noted facts, indicates that essentially the same materials continue to Buzzards Bay, the ancient series being interrupted only by the indentations which are formed by several "drowned" valleys and by Monument River. In a railway cutting just west of Buzzards Bay station there was exposed in 1896 a section about 4 feet deep which showed stratified ferruginous sands that were slightly folded. These beds appeared to belong to the same series as those at "Quisset" Harbor.

Just east of Falmouth the stream beds near the shore at several points reveal by a little excavating the presence of indurated ferruginous sands and gravels of the same type as those found north of Woods Hole. Moreover, the streams that drain from the eastern face of the Falmouth moraine show that the percolating drainage which is normal to a sand-plain country is interrupted by some resisting layers, which hold the water near the surface. If there were not water-turning beds under these sand plains they would, like those of the similar plains of Marthas Vineyard and Nantucket, drain by percolation to the sea.

The facts above noted warrant the hypothesis that the western section of Cape Cod, say for a strip some 8 miles in width, has a foundation of ancient sands, gravels, and clays which rises to a considerable height above the water level, and is, in parts at least, much dislocated.

It is barely possible that the unseen water-holding layers on the eastern side of this area are of till or other clay beds of Glacial age, but the improbability of this view will be made apparent by the account of similar deposits in other parts of the cape.

On the northern shore of the peninsula, from near Monument River eastward to Yarmouth, and less distinctly still farther eastward to Orleans, there is an often indistinct but clearly traceable slope leading upward from the sea level to a height of 60 feet or more. This slope is often more or less masked by local accumulations of till, or even by small ridges of a morainal nature; but wherever its structure is revealed it is found to be made up of a deposit of dark-blue and gray stratified clays. Its presence is generally attested by the fact that it is not penetrable by water, and the fields which lie upon it are quite different in character from those found elsewhere in the cape district. The agriculture of the northern portion of Barnstable County has indeed been to a considerable extent founded on the quality of this underlying material, which affords a much more enduring soil than is found elsewhere in the area.

Occasional wells on this northern slope of the cape, and particularly the brick pits in Barnstable, show this clay to have the thickness of at least 20 feet. At no point, so far as I have been able to find, has it been passed through.

The clay which so generally forms the northward slope of the cape, between Orleans and Monument River, apparently underlies all the characteristic deposits of the last Glacial epoch. Upon it rests a number of small areas of an evidently morainal nature, as well as a general though rather thin covering of till, which appears at some points, particularly at the brick pits above referred to, to be somewhat churned up with the lower clay. Nevertheless, the distinction between the two deposits is sufficiently clear to show that they are only accidentally associated. Although this clay is to a great extent masked by the usually thin coating of drift, it appears to be continued as a tolerably connected deposit from the western extremity of the cape to Orleans, and perhaps still farther eastward. The fields of this section owe their relative fertility in part to the fact that the clay keeps the water table nearer the surface of the ground and in part to the commingling of this clay with the glacial waste, which in this district is distinctly more clayey than it is in other parts of the cape.

The northern clay of Cape Cod does not appear to have been dislocated by compression strains, at least none such have been seen in the scanty sections which are exposed to view. As to the origin of the deposit, the evidence is not yet clear. So far as ascertained, the material contains no fossils. In its general aspect it is like the well-known brick clays of southeastern Massachusetts, which were, in some cases at least, clearly formed at the time of, and in front of, the glacial sheets during the last ice advances. Yet, as no pebbles have been found in

the deposit, and as its resemblance to some of the beds of the Nashaquitsa series of Marthas Vineyard, which clearly antedates the last ice epoch, is evident, it will not be safe to class it as of Glacial age. It is, perhaps, the equivalent of the Tisbury clays of Marthas Vineyard.

South of the glacial clays, and generally beneath the moraine which extends from Monument River to Orleans, the evidence, though imperfect, goes to show the existence of another series of clays, which exhibit a general likeness to those noted as occurring in Falmouth near Quamquisset Harbor. In my opinion this ridge of older clays forms the greater part of the considerable elevation, which at first sight appears to be entirely of a morainal nature. The evidence in support of this proposition is as follows:

Along the line of the moraine, which attains at several points an altitude of nearly 200 feet, we find that the depressions of the surface, up to 150 feet, often contain water for a large part of the year. Even where they are not temporary pools, these kettles commonly exhibit up to or above the last-named height a degree of wetness which indicates that they rest upon more impervious materials than the very porous moraine affords. An index of the same nature is to be found in the height of the considerable lakes, of which a score or more are shown on the topographical map of this part of the cape. Thus, Peters Pond, in Sandwich, is about 95 feet above the sea, and a number of the other lakes exceed 50 feet in altitude. In general, it may be said that the lakes in the central portion of the cape, particularly those within the limits of the distinctly moraine topography, stand at heights above the sea which clearly indicate that the barriers which retain the water are much less pervious than the sandy, pebbly, and bowldery matter of the moraine itself, which in this regard is but slightly more effective than the washed drift. The same considerations lead us to extend the clay area much to the southward of the southern face of the moraine. The lakes on the sand plains for some distance out from the face of the moraine lie at heights which exclude the supposition that their waters are retained by the interstitial friction or resistance to percolation which is normal to washed drift. On the sand plains of Marthas Vineyard the value of this friction, as is shown by the depth at which water has been struck in the central portion of the island, is not more than 2 to 3 feet to the mile. On Cape Cod many of these lakes of the plain are at heights above the sea which would afford grades of from 12 to 15 feet to the mile from their low-water mark to mean tide. On this account, as well as from the general statement which is had from all those who are familiar with the history of the wells of the district, that they usually strike clay before attaining the level of the sea, I judge that the central clays of the island probably extend some distance south of the moraine.

As to the character and altitudes of the central or submorainal clays of the northern part of Cape Cod, the evidence yet gathered, though

not extensive, is, taken with what has been found near Woods Hole, sufficient to show something of these conditions. In the section between Great Pond and West Barnstable the roads show some small sections of grayish-white bedded sands unlike any glacial beds known to me. The beds dip to the southeast at angles of from 8 to 10 degrees. Traces of reddish-brown clays are revealed in the same district.

In the town of Dennis, at the side of the State road, the cuttings at the time they were made revealed dark clays and gray sands, thinly bedded, resembling the Nashaquitsa series. These beds are folded on a north-south axis, the amplitude of the arches, so far as could be ascertained, not exceeding 50 feet. Although these foldings were not very plain, they were recognized by my companion, who had no special knowledge of geology, as arches having the form shown in the diagram, fig. 88.

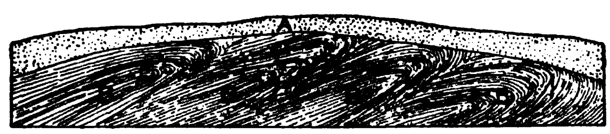


FIG. 88.—Diagrammatic section showing position of folded clays, State road, Dennis. A, glacial drift; B, folds in (Truro?) clays. 1 inch = 100 feet.

In the town of Brewster, about one-half mile east of the station of that name, there is a considerable area (100 acres or more) in which the drift covering is so thin that the under clays are revealed. These appear to be somewhat confused next the surface by the rubbing and scouring action of the glacier. It is thus impossible, in the slight exposures, to determine the exact attitude of the beds, which are of grayish and blue sandy clays and red clays, the last of the general aspect of those at Gay Head. Near Griffiths Pond—now a cranberry bog—a considerable exposure of the red clay on the north side of the road to the station shows not very clearly a rather steep dip to the northwest. Although the scanty showing of these clays in the small pits by the roadside does not afford distinct evidence of steep dips, the distribution of the outcrops indicates such attitudes, with a prevailing strike N. 45° E. These clays rise to about 100 feet above the level of the sea.

From Schoolhouse Pond to East Brewster station the clays, apparently of the same general nature as those last described, lie everywhere near the surface on the south side of the main road. The deposit rises to the height of from 100 to 110 feet above the level of tide. Its upper surface forms a tolerably gentle slope to the northward, on which rests the morainal heaps and into which the kettles seem to be cut, with the result that they are usually very wet at their bottoms. The red or reddish sandy clays appear also, though obscurely, in some of the roads of East Harwich which lie to the south of the section last described.

In Orleans the older series seems to be present thoughout the greater portions of the area of the town. It is scantily revealed in the road

cuttings, and is shown in an effective way only on the southwest side of Town Cove, just east of Tonset. Along this shore the deposits are not enough exposed to give a clear idea of their attitude. They are all dark colored and are related to the glacial beds in the manner indicated in the accompanying diagram, fig. 89.

The above-described clays appear to continue for some distance northward into Eastham. The precise line where they cease to rise above the level of the sea has not been determined; it can not be ascertained without pits or borings. It seems likely that this limit is not far from North Eastham station.

On the south side of the moraine there exists a series of clays which are revealed in the ordinary domestic wells that are driven in this section. I have been unable to find any of these wells in process of excavation, and am therefore limited as to information concerning the section to what I have been able to gather from various persons whose

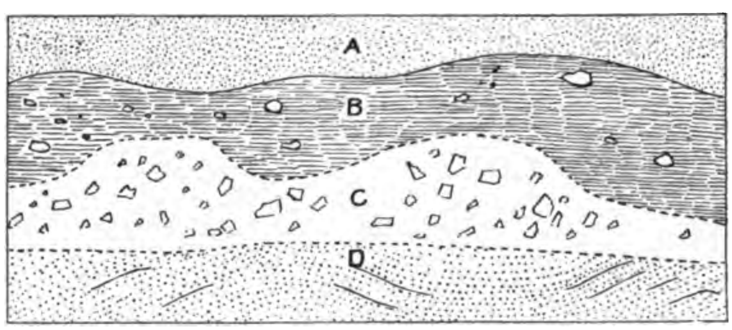


FIG. 89.—Diagrammatic section of post-Glacial clays, west side of Town Cove, one-half mile south of its head. A, glacial sands; B, stratified clays; C, till; D, folded clays and sands. 1 inch = 10 feet.

statements seem worthy of trust. These persons agree that for a considerable distance south of the moraine in Harwich, to within a mile or so of the sea, these wells strike a dark-colored clay ordinarily at a depth of 10 to 20 feet below the surface. This deposit usually has to be passed through in order to obtain water, which is found in thin layers of gravel above a lower-lying clay. The thickness of the upper clay is said to be 10 feet or more; the lower clay deposits do not appear to have been passed through.

The statements concerning the existence of a series of clay layers beneath the sand plain on the southern side of the Cape Cod moraine are in accordance with the evidence afforded by the levels of the lakes in this area. As before remarked, these lakes, especially those which are situated within 2 or 3 miles of the morainal area, have a height above the level of the sea which is inconsistent with the supposition that they are fenced in by no more effective barriers than would be formed of the open-textured sand and gravel of the plain in which they lie. These lakes are, in part at least, to be regarded as occupying old val-

leys, which slope down to the northward and have been barred across by morainal accumulations of a clayey nature, which have in good part effaced them.

As to the attitude of these clay beds, which lie beneath the whole or a large part of the southern morainal plain of the cape as far out as Orleans, there is no basis for accurate determination. The reports from those who have sunk wells in the area leads, however, to the supposition that the deposits are not dislocated after the manner of the central series, but lie in approximately horizontal attitudes, dipping gently to the southward. It is thus tolerably clear that the fundamental structure of the body of the cape—at least that part of it lying between Monument River and Eastham—consists of a central axis of more ancient clays and sands, having in part at least the general aspect of the Nashaquitsa series of Marthas Vineyard, and being likewise much disturbed by orogenic action. On the flanks of this older axis of elevation lie the clays, which, as before noted, appear to form the north and south slopes of the area, and on which rest the relatively thin layer of glacial waste—the moraines and sand plains which give the surface aspect to the region.

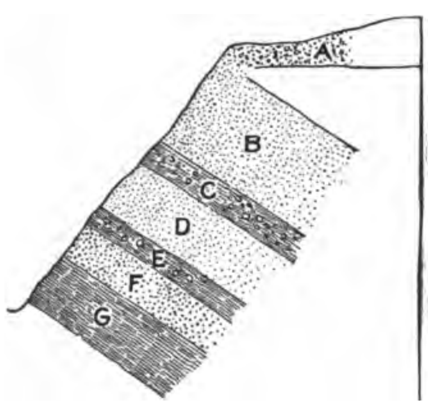
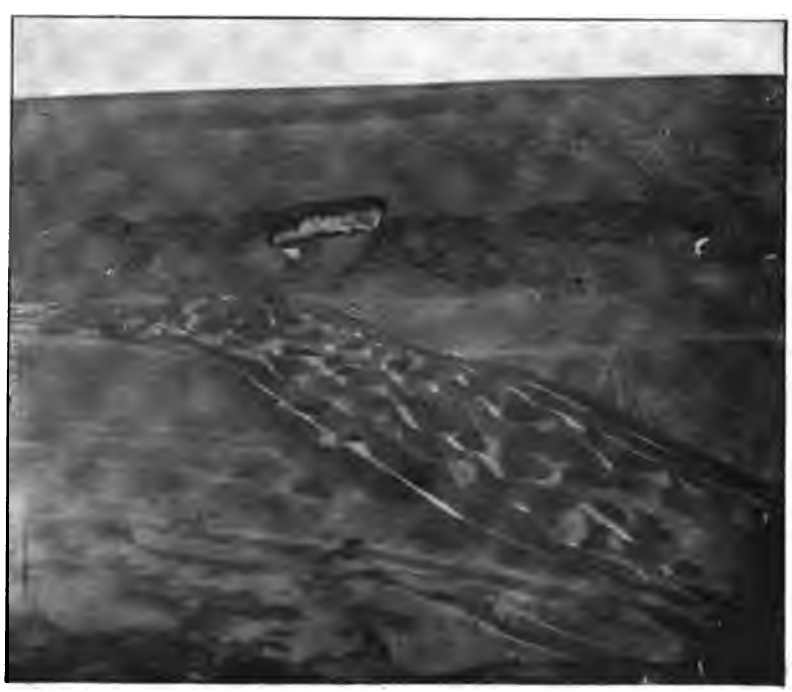


FIG. 90.—Diagrammatic section near Wellfleet bridge, in Truro. A, glacial drift; B, D, F, stratified sands; C, E, pebbly sandy clays; G, fine clay. 1 inch = 5 feet.

The outer portion of the cape—i. e., that between Orleans, or perhaps the northern portion of Eastham, and the extremity of the peninsula—has a structure which indicates a history somewhat different from that just noted. In this outer part the older dislocated beds with the red clay layers do not appear above the water level, or if they rise above that plane they are completely covered by the later-formed deposits of clays and sands. In this area we have a succession of beds, indicated in the accompanying fig. 90, which shows a series of events somewhat different from that exhibited in the district to the westward. In this section, from central Eastham to the end of the highland at Moon Pond and Salt Meadow Pond, the beds consist of certain clays which appear, so far as can be determined by their general nature and relations, to be essentially similar to those beds which were noted as occurring on either side of the Nashaquitsa series of the western district of the peninsula. Upon these clays occur beds of much-decayed sands and gravels, which in character are somewhat like those found in the subglacial portion of the section on the west side of Town Cove in Orleans. Owing to the large showing made by the glacial deposits of

A. DUNE POND, PROVINCETOWN.



B. NEAR VIEW OF DUNE SURFACE, SHOWING MASS OF BURIED SNOW.

this part of the cape, this series of sands and clays has been assumed to be the product of the ice age. Although the question as to the age of the several divisions of rocks of this field is in the main to be dealt with in a later part of this report, it may here be said that there is good reason to doubt whether the beds shown in Wellfleet and Truro should be reckoned as of glacial origin, at least in the sense that the sand plains in the more eastern section are to be so reckoned. They have exhibited no glaciated pebbles; they lack the surface slope so characteristic of morainal aprons, and they fail to exhibit the occasional large ice-rafted bowlders so common in such deposits.

From the northern end of the highland of the cape to the extremity of the peninsula the land is, so far as its surface is concerned, made up altogether of sands, which have been brought into their position by the recent action of marine currents or of the wind. As has been shown by Professor Davis, the form of the slope which terminates the elevated ground toward Salt Meadow Pond indicates marine erosion before the outermost part of the cape had been built. As will be hereafter noted in more detail, this agglomeration of sand hooks and spits most likely rests upon a portion of the land which had been cut away by a set of currents different from those now prevailing on this shore.

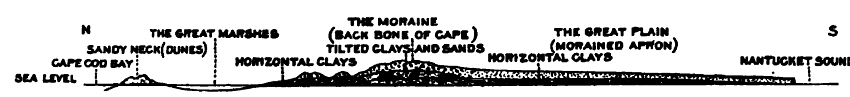


FIG. 91.—Diagrammatic section across Cape Cod from West Barnstable station to Osterville, showing the general structure of the area west of Orleans.

The construction work involved in the formation of dunes is admirably shown in this portion of the cape. By the exercise of a certain amount of care in planting, the local and State authorities have succeeded in arresting the movement over a large part of the area, but the seaword portion of it is still in constant motion. The speed of this movement may be judged by the fact that in April, 1897, a mass of snow 20 feet in length and 2 feet in thickness was revealed where it had been covered with sand during the preceding winter to the depth of 12 feet, the mass having been subsequently cut through by a change in the scouring movement of the wind. (See Pl. XCVII, *B*.)

The irregular deposition of the dunes has led to the formation of a number of small lakes, which, though of no geological significance, are very picturesque. They are generally bordered by a fine growth of scrubby trees, nourished by the moisture they afford, while beyond this fertile margin rise the desolate slopes of sand. (See Pl. XCVII, *A*.)

HISTORY OF THE CAPE COD SERIES.

As already indicated, the beds exhibited in this area may, so far as they have been interpreted, be provisionally divided into five groups, of

very unequal value as regards their extent or the time occupied in their formation. These groups are, in order of age, as follows:

First and lowest, the series of gravels, sands, and sandy clays which, on the basis of general aspect, are here reckoned as the equivalent of the Nashaquitsa series of Marthas Vineyard, and which, as on that island, have been subjected to a considerable amount of stressing.

Second, the dark-colored clays which are revealed at the brick pits in West Barnstable, at the base of the section on the west shore of Town Cove, at the base of the section at Highland light, and at various other points; these are known as the Barnstable series. These pits are occasionally much filled. Their position in relation to the other groups remains somewhat doubtful.

Third, the sands and clays characteristic of the Wellfleet and Truro district, found along the shore northward to Plymouth Harbor, and probably northward to Egypt or Coleman Heights, in Scituate. It is not unlikely that remnants of these beds occur in other portions of southeastern New England.

Fourth, the glacial deposits, including the morainal accumulations, the eskers, and the sand plains which lie south of the moraines.

Fifth, the beds formed since the Glacial period, consisting of dunes, spits and hooks, submarine coast shelves and shallows, and the organic deposits of swamps and marshes.

These five groups of deposits will now be considered from the point of view of their geological history.

NASHAQUITSA SERIES.

The identification of this series, as exhibited in Cape Cod, with that found at the typical locality on Marthas Vineyard, rests altogether upon the general, though close, resemblance of the physical characteristics of the deposits. In both we have the same gray measures—sands intermingled with sandy clays, which have a red or reddish hue; in both the pebbly element is scanty. In the Cape Cod exposures the red beds are more prominent than on Marthas Vineyard, but in both cases the hue is less pronounced and the clayey element less considerable than in the more ancient deposits of the Gay Head Miocene series. It seems likely that these reddish clays have in each case been derived from the washing over of the older Tertiary deposits. That such is the case on Marthas Vineyard admits of scarcely any doubt, for the reason that there the later beds contain fossils which evidently came from the erosion of the earlier series.

It is hardly to be supposed that these red clays of Cape Cod could have been derived from a field so remote as that of Gay Head. As may be seen at the last-named point, the eroded clay is not carried any distance by the tidal currents. We are, therefore, compelled to suppose that the beds in Cape Cod were derived from some areas of the Gay Head series which have been completely eroded away, or at least lowered

beneath the sea level by the wearing to which they have been subjected. The remnant of the Miocene rocks which exists in Marshfield, on the mainland to the north of Cape Cod, lies in a depression of the crystalline rocks, where it has been in a measure protected from erosion. It is eminently probable that these beds once occupied the district between Marshfield and the base of the cape. They may, indeed, have had a much greater areal extent.

The probability that the deposits of the series found at Gay Head and elsewhere on Marthas Vineyard once extended over a wide field in the cape district is made the clearer by the fact that remnants of the greensands, as is well known, occur at Marshfield, Massachusetts, north of Plymouth, and apparently also below the level of the sea in one or more points in the Monomoy group of shoals. The evidence as to the existence of the beds at the last-named point is incomplete, but it deserves a brief statement.

Among the shallows in the Monomoy area is one sometimes known as Stone Horse Shoal. This eminently curious name points to some peculiar feature in the history or structure of the place. I am told by Capt. John L. Veeder, of Woods Hole, that some years ago he was engaged in breaking up the wreck of a ship which had been for some time lying on that shoal and had become partly embedded in the sands. When the hulk rolled over it brought up a quantity of "dark sand" which contained many fragments of bones. In answer to my inquiry Captain Veeder stated that the material was like the greensands of Gay Head. It is well known that sailors are apt to class any bones as those of horses.

As to the nature of the erosion which provided the material for the Nashaquitsa series, there is little distinct evidence, and that is of a negative character. The beds on Marthas Vineyard have afforded fragments of magnetic iron ore, apparently from Cumberland, Rhode Island, and other materials which may be from the same field; but it is to be observed that the pebbles may not have been derived directly from that locality, but may have come, as is the case with much of other materials, intermediately from deposits of Tertiary or Cretaceous age. As these beds were apparently deposited not long before the advent of the last Glacial period, the question arises whether they indicate any form of ice action. To this inquiry a negative answer must in general be given. None of the pebbles are scratched or faceted; there appear to be no ice-rafted blocks; the fragments are all small, the greater part of them of quartzitic or felsitic nature, the ordinary crystalline rocks, such as are so plentifully exhibited by the glacial deposits of the last ice period, being of scant occurrence. In general the pebbles are much waterworn and affected by superficial decay, which shows that they have been long separated from their original bedding places.

The transportation of the materials of the Nashaquitsa series appears

to have been effected, in part at least, by strong and variable currents, as is shown by the stony cross bedding of the sands. At other times, and with sudden alternations, the conditions were such as allowed the deposition of fine-grained clays in these layers. It is a noteworthy feature of the formation that it contains, so far as ascertained, no indigenous fossils of a recognizable nature. This, taken in connection with the fact that on the west end of Marthas Vineyard (where alone the series is well exhibited) there are a great many organic remains of animals derived from the Tertiary rocks, goes to indicate that, though the conditions of deposition and of subsequent time favored the preservation of fossils, none were contributed to the formation by creatures living in the waters. This inorganic aspect of the beds may be due to any one of several conditions existing in this district at the time of their formation. It may have been due to the presence of a glacial sheet; but this hypothesis is less warranted than is the supposition that the deposition took place rapidly in a fresh-water basin much in the manner in which deposits are now accumulating in the basins of certain great lakes, as, for instance, in Lake Ontario near the mouth of the Genesee River. The evidence afforded by the beds is, indeed, most consistent with the view that they were thus formed in a fresh-water or estuarine body into which large and sediment-laden streams were discharged.

At first sight the supposition that this portion of the continent was the seat of considerable lakes during or about the Pliocene epoch may seem to require an excessive difference from the existing geographical conditions. It is, however, evident that the Atlantic shoreland from the Carolinas to Nova Scotia has from the beginning of the Mesozoic to the present geological time tended to develop extensive lacustrine areas. In Triassic time these areas of fresh water were numerous and large, the basins having a character and an extent comparable with those of the eastern flank of the Rocky Mountains during the Cretaceous period. A part at least of the Gay Head series, including the plant beds of the Cretaceous and a portion of the Miocene, appears to have been deposited in areas of fresh water. It is not necessary to suppose that these areas of fresh water were completely separated from the sea; they may have been estuarine in their nature, much as are the sounds of North Carolina and other portions of the southern coast of the United States.

The question arises as to the original extension of the deposits of the Nashaquitsa series. As yet they have been definitely observed only on Marthas Vineyard, in the islands of the Elizabeth Archipelago, and in the area we are now considering. It is likely, however, that beds of equivalent age exist in Block, Fishers, and Long islands. Deposits of perhaps the same age may exist farther to the south, though until fossils are found in the Massachusetts area there will be no sufficient means of fixing the age. The fact that these beds are found scattered over a considerable area in the manner before noted indicates

A. SECTION OF PART OF TRURO SERIES ON NORTH SIDE OF PAMET RIVER, NEAR BRIDGE.

B. VALLEY EXCAVATED IN TRURO SERIES, CHILTONVILLE, PLYMOUTH.

that they were at one time extensive. The height they now occupy, notwithstanding the considerable erosion to which they have been subjected, shows that they must have been formed when the level of the sea was much higher than at present. Thus on Marthas Vineyard they lie at not less than 200 feet above the tide, and their upper surface has shared in the erosion which has served to develop an old and deeply incised topography on the area. It is, indeed, necessary to assume that the upper surface of the deposit originally lay at a far higher level, perhaps 100 feet or more above its present plane.

As to the dislocation of the beds, this seems to have occurred before the erosion which formed the valleys in which lie the bays and sounds that separate the known location of the deposits. The time of the dislocation can not be more definitely stated than that it was after a part, at least, of the Pliocene had been deposited and before the deposition of the Barnstable clays or the Tisbury beds, which apparently lie above them. The interval between these stages was evidently of considerable duration, even in the geological sense of the word, for it included not only the time occupied in the folding but also the period required for a considerable erosion of the beds.

Concerning the extent of the dislocations which have affected the Nashaquitsa series, it may be said that it was much less intense and general than that which is recorded in the Gay Head section. In the area occupied by the last-named group of strata, about 30 square miles in extent, the average dip of the beds is about 45°, and no part of the layers, so far as seen, remains in a horizontal attitude. In the case of the Nashaquitsa series the greater portion of the Marthas Vineyard area is but little dislocated, and on Cape Cod the average departure from the original horizontal attitude is apparently only a little greater than it is on the Vineyard, probably not averaging more than 10° of declivity.

The foregoing considerations justify the supposition that the Nashaquitsa series originally occupied an area along this portion of the shore of the continent; they warrant also the belief that this area was, after a slight though distinct dislocation, carved into an extended topographical relief and that the surface of its more salient points was considerably lowered in the process. We have to suppose that this carving was, in the main at least, due to river action, though the valleys may have been affected by marine agencies after they were lowered beneath the plane of the sea.

THE BARNSTABLE SERIES.

After the formation of the topography cut in the Nashaquitsa series had been effected the district was again depressed beneath the sea. The downward movement certainly brought the coast line at least 100 feet above its present level, for the Barnstable clays attain the elevation of 60 feet above tide, and the Tisbury clays, their probable equiva-

lent, rise to about 90 feet. As these clays, particularly those of the Barnstable area, have the character which belongs to deposits formed at some distance from the shore line, it is likely that the down-sinking was to a much greater depth than is here indicated.

Clays of the same general nature as those of the Barnstable series occur along the shore to the eastward as far as Chatham, though the best exposures known to me are those on the present marine escarpment and in the clay pits at Barnstable; there they seem everywhere to underlie the glacial deposits, being usually separated from them by a variable thickness of apparently pure glacial sands and clays.

It is not unlikely that some of the brick clays lying farther northward and westward on the mainland, as well as other deposits in Harwich, are of the same age as those of the Barnstable series, but their discrimination is difficult and has not yet been effected for the reason that they do not apparently differ in any distinct way from those of later date and of undoubted glacial origin.

The gravels in the clays of the Barnstable series are known to me only by the reports of those who have penetrated the beds in sinking wells. They are described as composed of small pebbles, mingled or coated with iron oxide.

The Barnstable beds, as has already been suggested, may be the equivalent of the Tisbury beds of Marthas Vineyard. The evidence of the identity of age is, it must be confessed, not very strong. It rests altogether on the fact that in both cases clay beds not greatly disturbed by the mountain-building forces rest upon the disturbed Gay Head series, and that they have both been elevated to a considerable height and carved by erosive agents. To suppose that the two series are of diverse age would require the assumption that there had been one more cycle of erosion, subsidence, and elevation in the Pleistocene period, which is already overcrowded with actions of this nature that I have been compelled to postulate in order to explain the geological structure of the district.

As against the supposition of the identity of age of the two sets of beds, it may be said that the Tisbury series forms a distinct, though much eroded, bench on the north side of the island of Marthas Vineyard. There is no evidence that they ever had a very wide lateral extent. The beds are mottled yellow and bluish clays and sands, with occasional bowlders of small size, which may possibly have been ice-rafted to their present positions. The materials of the strata have apparently been derived from the erosion of the Cretaceous and Tertiary beds of the dislocated area against which they lie. It seems quite possible that with the advance of our knowledge of this district it will be found that the Barnstable beds, which appear to have been formed in deep water in an offshore position, are not to be regarded as in age the equivalents of the Tisbury beds, which were evidently formed nearer the shore and in a shallower depth.

A. STREAM CHANNEL CUT IN CONTORTED CLAYS, NORTH WARWICK STATION.

B. HILL NEAR CHATHAMPORT; TRURO SERIES, DRUMLOID OUTLINE.

It is to be understood that evidence of a diversity in age of the glacial clays and of the beds here referred to as related to the Barnstable series is not perfectly clear. I see no reason to doubt that the formation of the deposits which lie beneath the cape and the region to the northward as far as Plymouth Harbor clearly antedate the last ice epoch, but some of the clay beds of the cape district may have been deposited during the time when the ice work was in progress. It should also be noted that even if the glacial origin of the Barnstable series should be proved, the evidence is still to the effect that the ice action was not that of the last advance, but an epoch separated from it by events which indicate the lapse of a great interval of time. This will be more evident in the sequel.

TRURO SERIES.

The characteristic Truro series is even more generally concealed than are the beds which lie beneath along the eastern shore from Wellfleet to Highland light. They are, it is true, revealed in the wasting cliffs, but the amount both of slipping and of loose débris is so great that it is not possible to determine further the character of the section than that it is composed of a hundred feet or more of fine, gray, micaceous sands and sandy clays in frequently alternating beds. These beds apparently contain no fragments of compound rocks; the only pebbles they carry—and these are small and of infrequent occurrence—are composed of white quartz. The beds appear to be somewhat disturbed, but the irregular sliding of the cliff as it is undercut by the sea makes this apparent evidence of orogenic stress untrustworthy.

At only two places has it as yet proved possible clearly to ascertain the true attitude of the beds in the Truro series. One of these is a pit whence clay for hardening roads has been taken. It is on the north side of Pamet River, immediately south of the road, and a few hundred feet from the bridge over that tidal stream. The section is as shown in Pl. XCVIII, *A*, and in fig. 90, p. 534. The materials consist of alternating clays and sands, such as are shown on the cliff at Highland light, even bedded and quite without pebbly matter except bits of rounded quartz. They lie at an angle of about 18°, dipping northwestward. There is a thin layer of pebbly drift on the top of the section. (See Pl. C.)

Another exhibition of these beds is in a clay pit 200 or 300 feet north of South Wellfleet station. Here the beds are at higher angles than in the section near Pamet River bridge; in part the slopes are of 30° or more. The bedding, indeed, seems to be crushed as it is at certain points on Marthas Vineyard. Here, as in the last-named section, there is a thin overlay of pebbly washed drift, with small rounded bowlderets.

It should be noted that the sections above described were obtained at the only points where the attitudes of the Truro series could be clearly discerned. Taken in connection with what has been observed on the cliff shore and in a considerable number of obscure artificial

exposures, there is evident reason for believing that the strata of this series are generally dislocated much as are the beds of Tertiary age on Marthas Vineyard.

It appears to me unreasonable to suppose that the steep dips of the beds of the Truro series are due either to cross bedding or to glacial thrusting. The sections examined are sufficiently extensive to reveal the true structure. They show nothing to arouse the suspicion that these slopes are due to deposition on the construction point of the stratum. As for the thrusting, there is, as is elsewhere noted, no good reason to believe that the glacier ever eroded this surface. If it did so, its action was not vigorous enough to have eroded the delicately molded pre-Glacial topography.

The feature which most distinctly separates the surface aspect of the Truro sands from that of the morainal aprons is their slope. This is not, as in the sand plains of Barnstable and elsewhere, toward the open sea on the east, but distinctly toward the bay on the west. The surface is, it is true, to a certain extent encumbered by the waste left upon it in the last advance of the ice; but making allowance for this coating, it is quite evident that the slope, instead of being outward from the ice front, was inward toward the face of the glacier. If, indeed, the deposit is to be regarded as a sand plain, it will have to be assumed that the ice lay outside of the cape, discharging its waste westward toward the bay, a view which is manifestly inconsistent with all we know of the distribution of the glacial envelope on this part of the shore.

Taking no account of the deformations of the surface in Truro and Wellfleet, which have been brought about by the small amount of glacial waste which the area bears, the westerly slope is clearly indicated either to the eye of the observer in the field or by the inspection of the topographic map, where the contours are seen to lower as we pass from the outer or eastern to the inner or western side of the area.

As we pass from the eminently characteristic surface of the sand deposits of Truro and Wellfleet toward the southern and western parts of the cape, the glacial deposits thicken and become more irregular, until in Orleans the Truro sands are to a great extent concealed by this drift. Nevertheless, beds of the same general nature are noticeable at most points where a natural or artificial section is carried to any considerable depth in all the area as far west as Yarmouth. They are particularly well shown in Dennis and Harwich, and are also revealed in the southern parts of Brewster and the northern portion of Harwich. It is here, as in the typical localities of the series, quite evident that the surface was deeply incised by the action of streams before the last invasion of the ice, which served to encumber and at times efface the preexisting valleys, though the erosive action which conveyed this waste was not sufficiently intense to cut away this rather delicately molded topography. Throughout the area in which these

A. TALUS SLOPE, HIGHLAND LIGHT.

B. CONTORTED TRURO CLAYS AND GRAVELS NEAR CHATHAMPORT.

ancient sands are traceable they generally rise on the crests of the ridges which they occupy to the height of about 100 feet above the level of the sea. It seems likely that while glacial erosion, mainly if not altogether due to streams from beneath the ice, may have cut down these crests to a certain amount, the extent of this wearing has probably been not more than a few feet.

The original extent of these Truro sands is, on account of the erosion to which they have been subjected, not clearly determinable. It seems, however, to have been great, as will be seen from the following notes concerning the distribution of beds apparently of that age which occur in a fragmentary manner in and about Cape Cod. In the western part of the cape there is reason to suspect that deposits of this age underlie the ridge of the Falmouth moraine. Exposures of yellow sands are shown at a number of points on the western face of the moraine in positions which indicate that they are portions of a large area which extends beneath this mass and rises to a considerable height beneath it. On the island of Naushon, the northernmost of the islands of the Elizabeth Archipelago, orange-colored sands with characteristic absence of coarse waste underlie nearly, if not quite, all of the area and rise to the usual height of about 100 feet. Southward throughout this group of islands to Penikese beds of this character and presumably of the same age are seen here and there, evidently lying in the Nashaquitsa series. On Marthas Vineyard the series is less well shown, yet it is tolerably well indicated on the northern side of the island at Copoggan Head (misnamed on the maps Cape Higgon), as well as at other points between Menemsha Creek and West Chop. They are also seen in the retreating escarpments of East Chop and West Chop and the sea face at Cottage City.

Beneath the great plain of Marthas Vineyard, the upper portion of which is clearly of the character proper to morainal aprons, there is revealed by occasional wells extending to the depth of 70 to 90 feet a deposit of yellow sands with no large pebbles, which appears to belong to this group. Here we have to suppose that the beds had been worn down by marine or other action to a level somewhat below that which they occupy elsewhere and then sheeted over with the deposits formed during the last advance of the ice. In the valleys of Tisbury and Tiasquan rivers, in the central part of Marthas Vineyard, and at Gay Head there are traces of the same sands, which are scantily revealed and only discriminable from the deposits of the Nashaquitsa series by the characteristic yellow hue.

West of the base of the cape, along the southern shore of Massachusetts, deposits which may be compared with those of the Truro series are not clearly disclosed and may not exist, though the search for them has not been carried so far as to make their absence certain. In Rhode Island, as has been suggested to me by my colleague, Mr. J. B. Woodworth, beds of this age may underlie the Charleston moraine, where,

as remarked by the late J. D. Dana, stratified sands appear to underlie the morainal deposits. The scanty outcrops of these beds in their appearance warrants the supposition that the formation has the same general character that it exhibits in the localities before described.

North of Cape Cod, along the shores of Massachusetts Bay, the Truro sands, overlain by distinct glacial deposits, are abundantly exhibited. On the shore of southern Plymouth, from point to point, they form the marine escarpment. (See Pl. CIV.) In the high ridge of Manomet Hill they probably attain the height of 250 feet or more above the level of the sea. The erratics, which are so abundant on the ridge and which give it the character of a moraine, form only a relatively thin coating on the summit of a pre-Glacially-formed ridge, resulting from extended subaerial erosion of the inferior sands. (See fig. 92, p. 555.)

North of Plymouth the curious table-land known as Egypt Heights, in the southern part of Scituate, appears to be composed of beds in character quite like those at Truro. The general form of this curious deposit of sand can best be explained by the supposition that it is the remnant of a large area, and not a local deposit accumulated during the last Glacial epoch. This view is supported by the general character of the material, which is much the same as that of the Truro section, though it is more deeply covered with recent glacial waste. Scattered patches of the same decayed sands continue to the northward as far as Boston Harbor. In that basin, mostly below the level of the sea, a thick deposit of sands clearly antedating the last ice epoch has been revealed by artificial sections, as in the tunnel for the Moon Island sewer, and particularly in a well boring made on Deer Island. At the last-named locality a thickness of 300 feet was passed through, the beds being in general character like those before described, except that the oxidation was less complete than at the other parts. The evidence goes to show that here, as elsewhere, this section of decayed sands with few pebbles is immediately, though discordantly, overlain by the bowldery drift. North of this point on the shore I am not aware of any sands which may be referred even conjecturally to the Truro series.

In the district of southeastern Massachusetts, remote from the shore, I am aware of but one locality where deposits of much-oxidized sands having the general character of those before described are clearly revealed. This is at Prospect Hill, in the southern part of the town of Raynham and the western part of Taunton. At this place we find an irregular ridge, composed mainly of sands with a few pebbly beds, capped in part by a layer of bowldery nature, which gives the mass something of the aspect of a moraine. Some years ago I came to the conclusion that the greater part of this ridge represented a much-eroded deposit, which was formed before the last ice advance and which had been scantily affected by a morainal accumulation made

TRURO SERIES AND GLACIAL BEDS, HIGHLAND LIGHT.

in that stage of the Glacial period. It now seems most reasonable to regard this as a remnant of the deposits of the Truro series.[1]

It is probable that many other deposits of well-oxidized sands which exist in southern New England will eventually be found to represent the same epochs of Pleistocene time as those above catalogued. At present they are naturally, and it may be inextricably, confused with the accumulations of washed drift which were so plentifully formed in front of the ice during the later advances of the glacier. As will be further noted in the study of the glacial deposits of Cape Cod, the Truro series may possibly be but the outer remnant of a broad sheet of shore sands formed during the earlier epochs of the Glacial period, when the margin of the ice lay at some distance north of the present shore, and that this moraine accumulation passed into other types of glacial waste as it approached the ice front.

The facts before noted make it probable that at some time before the advent of the ice of the last Glacial period in the region about Cape Cod the surface of the land was at a much lower level than it is now—at least 100 feet lower—and that at that time an extensive sheet of water-borne sands was deposited on the sea bottom. It seems necessary to suppose that this sheet was laid down as a tolerably continuous outward-sloping formation, such as is now found in the continental shelf along the Atlantic coast. It certainly could not have accumulated in the patches and ridges in which it now appears. We can not, for instance, suppose that the crest which forms the foundation of the Elizabeth Islands, and which rises about 150 feet above the present level of the sea floor, or that of the Truro Plateau, which attains a like or greater height above the bottom of Cape Cod Bay, was formed as we now find it. We are forced to assume that these evident remnants of erosive work were originally parts of a widespread deposit, by far the greater part of which has been swept away.

The time of the erosion of the Truro sands, which reduced the area of the formation to the few remnants we now find, clearly antedated the last advances of the continental glacier. This is indicated by the facts that the position of the remnants is that which they would occupy if they were left by water erosion, but not such as would exist if the wearing had been effected by ice, and that the preexisting rather delicate topography, such as would have been carved by stream action, was not destroyed by the glacial erosion. In illustration of the first of these points it may be said that the ridge of the Elizabeth Islands is precisely such as would be brought about if it had been a divide between the supposed rivers of Buzzards Bay and Vineyard Sound, but in no way could it well be explained by glacial or marine erosion. As for the second, the many pre-Glacial channels on the Truro-Wellfleet plains show how even delicately sculptured valleys were not completely

[1] Since this report was written beds apparently the equivalents of the Truro series have been found by the writer at a number of points in southeastern New England.

defaced by the wearing influence of the glacier which came upon them in its marginal and attenuated form, if indeed they were ever actually beneath the ice.

As for the time when the erosion of the Truro sands was effected, we may confidently place it in the later part of the long interval which is partly, at least, recorded in the well-developed subaerial topography which was made on Marthas Vineyard after the cessation of the dislocation of the underlying beds and before the advent of the ice of the last Glacial epoch. As before remarked, this interval was long, for the work done during it was vast. It is clear that the Truro beds were formed after this topography was pretty well completed, for beds referable to the age lie partly in the valleys due to the erosion in question. It is thus evident that the greater part of the erosion of these later sands came after the shape of the Vineyard topography had been in large part determined, but probably before the valleys thereof had attained anything like the present development. (See Pls. CII, CIII.)

The reduction to a plain of the Truro sands was probably in part effected by the action of the sea. As may be noted along the shores where these beds are subjected to the action of the waves and marine currents, the beds wear away with exceeding rapidity. It may, however, have been in considerable part accomplished by ordinary stream action, as is shown by the persistence of many ancient valleys in those parts of the cape district underlain by these deposits. It is, however, difficult to believe that this stream erosion took place under the present conditions of climate and geography, for the reason that the beds of these ancient water ways are no longer occupied by streams, except, perhaps, on the rare occasions when, on a frozen earth, melted snow or rain is deprived of its usual exit by percolating into the porous underlying sands. The absence of water in these channels is probably to be attributed in part to the fact that they have been greatly shortened by the cutting away of their headwaters, so that the water now flowing seaward in their drainage is less in amount than of old, being no longer more than can pass through the interstices of the sands, through which it more readily finds a passage because the way to the sea is not so long as of old. It is probable, however, that the amount of the rainfall has in geologically modern times diminished in this region, as elsewhere on this and other continents, so that the capillary channels are able to afford storage and passage to all the precipitation. It may be observed that in times of any great rainfall sandy plains occasionally for a short time develop superficial streams, the water quickly ceasing to flow when the precipitation stops.

The rate of the erosion of the Truro beds wherever they are assailed by either marine or fluviatile agents is made the greater by the fact that the beds are destitute of coarse débris, which, in the case of the till, brings about the formation of a more or less effective revetment on the erosion face that hinders the action of waves or currents.

A. MOON POND ESCARPMENT, FACING PROVINCETOWN SPIT.

B. BEHEADED WATERLESS VALLEY JUST SOUTH OF HIGHLAND LIGHT.

Moreover, the very lean nature of the soil causes the growth of vegetation to be slight in amount, so that the protection of this sort which is usually so important is scanty. Thus the wearing rate on this group of deposits is likely to be very much greater than it is on such beds as form the Tertiary strata of Marthas Vineyard, frail as the latter appear to be. (See Pl. XCVIII.)

The most important indication pointing to the origin of these Truro sands is the apparently entire absence of fossils in the section. In the extensive outcrops which I have inspected no trace of organic matter has appeared. It seems clear that the beds were laid down under conditions which were peculiarly unfavorable for the inclusion of organic remains, or that such remains were subjected to some process which utterly removed them. Although, as before noted, these beds are considerably oxidized, it can not well be believed that fossils once present have been utterly destroyed. The Tertiary sands of Virginia and elsewhere are equally affected by decay, yet the mulluscan remains are fairly well preserved. Assuming, then, that these beds were originally formed without organic remains, the probability is fairly established that their materials were brought into the sea by glacial action. In no other way does it seem possible to account for the formation and deposition of such a mass in a marine or lacustrine area. It is to be said that this view has its difficulties, among which we may reckon the apparent absence, as before noted, of all ice-rafted blocks in the beds and the lack of clay in the greater part of the section.

Taken in connection with the seemingly nonfossiliferous clays of the Barnstable series, the Truro beds may perhaps be regarded as a stage in one of the several cycles of a glacial period. It is a well-recognized fact that the glacial flour or fine débris, which in the ordinary course of glaciation constitutes the larger part of the detritus that is formed, is normally carried much farther away from the front of the sheet than the sand, and that this in time goes farther than the pebbly matter. We may thus reckon that the Barnstable clays are the outer or relatively remote accumulations of an ordinary glacier, and that the Truro sands were laid down when the ice front was nearer the present shore line. If this view be accepted, we must then suppose that in the ice epoch which brought about the formation of this series—probably not the last Glacial epoch—the glacial sheet did not quite attain to this field, and that the land lay at a lower level than it does at present. As is clearly indicated by the extensive erosion which followed this period of deposition—erosion in which the glacier appears to have had no part—the time intervening between the formation of the Truro beds and the advance of the ice sheet which deposited the till, moraines, kames, etc., of the district must have been great. It was assuredly many times as great as that which has elapsed since the last of the ice sheets left the field.

Although the matter has been before stated in a fragmentary manner,

it may be well again to call attention to the accumulation of evidence which exists in this field going to show the very great length of the time which has elapsed since the close of the Pliocene. In this interval there were evidently three distinct periods of erosion, each of long duration, and an equal or greater number of widely varying changes in the position of the land in relation to the sea. As measured against the geological work which was done in these periods, that brought about since the close of the last ice advance is relatively of little account, being limited to slight changes of level and to a small amount of marine cutting, the subaerial wearing being quite insignificant, perhaps not the one-hundredth part of what was done in the earlier stages of the so-called post-Tertiary. It thus seems that, basing the measure on a vaguely assumed rate in the alteration of organic forms, we have most likely much underestimated the duration of this division of the earth's history.

CONDITION OF THE DISTRICT AT THE BEGINNING OF THE LAST GLACIAL EPOCH.

The conditions of height and shape of the land in this area immediately before the advent of the ice of the last Glacial epoch appear to be approximately determinable. It is tolerably evident that the land lay at a higher level in relation to the plane of the ocean than it does at present. This is indicated by the existence of the flooded drainage basins, which have been already in part described. These drowned valleys include not only the greater basins of Cape Cod Bay, Nantucket and Vineyard sounds, and Buzzards Bay, but many of the divisions or branches of these wide valleys where the streams tributary to the effaced rivers now enter the sea. Thus, on the islands of the south as well as on the mainland all the valleys which are now or have been in former times the seats of streams are flooded at their mouths.

On the north shore of Cape Cod we find a number of pre-Glacial channels which slope toward the bay of that name, and which evidently were at the time of their excavation the beds of streams discharging into a river that flowed northwardly to the shore line, which was farther out seaward than at present. These old valleys may be traced from Duxbury to the northern part of Truro. They point toward the central portion of the submerged trough in a normal and most suggestive manner. On the body of the cape these channels are generally much occluded by the deposits of glacial drift. They are to a considerable extent deformed by the scouring action of the streams which flowed beneath the ice sheet while it lay over the country.

The first of these channels of Cape Cod to be noted is that of Monument River, which now is a tidal stream discharging into Buzzards Bay. As it is clogged at its northern end by drift, it appears as a tributary of the ancient stream which occupied the valley of Buzzards

A. TOPOGRAPHY CHARACTERISTIC OF THE TRURO SERIES; VALLEY OBSTRUCTED BY GLACIAL DRIFT.

B. BLUFFS OF TRURO SERIES, PAMET RIVER VALLEY.

Bay. The form of the trough, which distinctly widens to the northward, suggests that it originally flowed into Cape Cod Bay, and that the ridge which originally parted it from the waters of the south was cut through by a torrent which flowed through this depression in the time when the basin to the north was occupied by the glacier. Eastward along the north shore of Yarmouth the streams appear to have been short and to have drained north and south from the highland now covered by the moraine, and which is locally known as the "Backbone of the Cape." The valleys of these streams draining northward are now but faintly traceable in the confusion of the morainal drift. On the south side of the ridge the valleys are to a great extent lowered beneath the frontal aprons of stratified materials, yet they may be indistinctly and in a general way traced by the depression in which lie the lakes and the streams which drain them.

At Bass River we have another instance in which a pre-Glacial valley (or valleys) has been enlarged and deepened by a current from the glacier. At this point there seems originally to have been two streams, one flowing northward, the other southward. The subglacial stream cut through the ridge between them, converting the trough into a broad way, which practically divides the cape, so that a trifling expenditure would suffice to make a water way from the north to the south side of the peninsula.

East of Bass River as far as Orleans the central ridge of the cape continues; the valleys become less and less blocked with till and morainal waste. This is especially the case on the north side, where the valleys in Dennis and Brewster channels, with rather obscure digitations pointing toward Cape Cod Bay, may be well traced. Beyond Orleans the ancient central watershed disappears, the sea having eaten into it from the east, and the larger valleys usually run across the width of the peninsula. This feature is best shown at Pamet River (see Pl. CIII), where one of these depressions appears—after the manner of the valleys of Bass River and Monument River—to have been depressed and widened by a glacial stream until it completely divides the peninsula, so that there is only a sand beach at the outer side to unite the farther part of the cape with the body of the area. There are, however, many lesser valleys which slope to the northward and which seem essentially river ways, though they are no longer occupied by streams. These troughs appear to be beheaded at their upper or outer ends, their conditions suggesting that their headwaters lay in the lost territory which has disappeared by recent marine erosion (see Pl. CII). In the account of the Truro beds it has been suggested that the former presence of streams on these now dry valleys may be accounted for by the above-suggested diminution of their drainage area, or perhaps in part by the diminished rainfall which appears generally to have attended the disappearance of the glacial sheet and which may have been the cause of its shrinking.

It is evident that the shape and size of Cape Cod shortly before the time when the glacier came upon it differed greatly from what we now find. In place of the narrow peninsula, in form like the flexed arm of a man, was a broad salient which extended as a connected land to some distance beyond the outer margins of Nantucket and Marthas Vineyard. At this stage the sea level probably stood about 200 feet lower than it does at present. During the time when the ice lay over the district it was depressed to a level at least 100 feet below where it now stands. This permitted the formation of the great sand plains of Marthas Vineyard, Nantucket, and the cape. When the ice departed the land in part resumed its old height, rising a little above its present elevation, and then sank, as is shown by the submerged forests which occur from point to point along the shores.

GLACIAL HISTORY OF THE DISTRICT.

It has already been noted that the deposits contained in the strata from the Miocene to the Truro series, inclusive, suggest the existence of glacial action in this part of the world at various times since the middle Tertiary; but unless the lower Pliocene beds of Gay Head attest the actual presence of ice, there is no reason to believe that it ever rested upon this field until the last epoch. Even in that time the sojourn of the glacier was evidently brief and the work which it did of relatively slight structural or geographical importance. It has already been noted that the general character of the surface had been determined by pre-Glacial conditions The valleys and ridges existed in general about where we now find them, only now they are to a great extent filled with glacial waste.

It seems pretty clear that immediately before the advent of the glacier the surface of the cape was carved into a topography such as is likely to be formed on clays and sands by the headwaters of streams. The valleys were rather deep and steep-sided. Where the clays come to the surface these valleys appear to have had something of the sharpness of the "bad-lands" topography of the western country. This is shown by the indented character of the old surface of the Nashaquitsa beds on Marthas Vineyard, where it is revealed in the coast sections. It is indicated on Cape Cod by the sharp ridges of clay, the so-called "pounds," which occasionally appear at the surface, projecting through the thin envelope of drift. The generally slight value of glacial erosion in this district is best shown on the island of Marthas Vineyard, where, as noted in previous reports, the wearing has been so slight as to leave the pre-Glacial topography essentially undisturbed except by the filling of the valleys with detritus.

On Cape Cod the actual erosion work is little if at all greater than on the islands of the south except in the case of the valleys which were cut through by the streams flowing from beneath the glacier or

A. SHORE BLUFF SOUTH OF SHIP POND, PLYMOUTH, SHOWING TRURO SERIES DIPPING STEEPLY NORTHWARD.

B. SHORE BLUFF SOUTH OF SHIP POND, PLYMOUTH, SHOWING TRURO SERIES FOLDED AND FAULTED.

under the roof of ice. Of these the most characteristic examples are Monument and Bass rivers. The channel of Pamet River is perhaps another example of the same nature.

There seems no evident reason why the subglacial streams which were on their way to the open water of the ocean should have climbed the ridge of the cape on the south in place of turning directly to the east around its extremity, which was then some distance south of the site of Provincetown. In view of this departure from the most direct way of escape, it may be suggested that as the ice fell back to the northward it may for a time have inclosed a lake between its retreating face and the concave north shore of the cape. In this case breaches would naturally have been formed to permit the discharge of this water from the melting ice through to the sound on the south. It is, however, not certain that any part of the cape was above the level of the sea at the time when the retreat of the ice took place. The only strong point in favor of the view that these channels were glacial stream beds is the fact that they are cut down to the sea level practically throughout their whole length, and that their forms indicate the passage of a current from the northward, and in the case of Monument River there is a considerable area of stratified sands near its mouth, on Buzzards Bay, which may well be taken as the delta formed where the current poured into that basin.

DIRECTION OF THE ICE MOVEMENT.

As the rocks of Cape Cod and the neighboring parts of southeastern Massachusetts are not of a nature to receive glacial scratches or groovings, the only indications of the direction of the ice flow are those afforded by the positions of frontal moraines and the direction in which erratics have been transported. It should be said that the moraines in this section present such discrepant evidence that conclusions drawn from their positions are not trustworthy. The transported blocks, therefore, furnish our only information, and this is in the main unsatisfactory.

In the western section of the cape, from Monument River to Orleans, the common petrographic elements of the moraine and till are granitites and the dike stones associated therewith, such as are found on the mainland. As these rocks occur along the shore from the parallel of Plymouth to Cape Ann, and may extend an indefinite distance eastward along the sea bottom, no precise evidence as to the course of the ice is to be obtained from these fragments. Eastward from the base of the cape there appears to be a constant increase in the amount of rocks of more evidently volcanic origin, such as are found sparsely about Cohasset and along the north shore of Massachusetts Bay. The deposits of this nature on the mainland are rather too limited to have afforded the large quantity of waste that appears in the cape. It seems likely that they have been derived from beds which lie beneath the sea.

So far as this evidence goes, it seems to show that the direction of the glacial movement on Cape Cod probably did not depart from the general trend indicated by the scratches observed at the nearest points on the mainland, or between north and north 30° west.

ENERGY OF THE ICE MOVEMENT.

As has been already noted, the energy of the glacial erosion in this district appears to have been but slight. It did not suffice to wear away a rather delicate antecedent topography. On the western part of the cape the transporting power of the ice was sufficient to carry a great number of erratics, many of which are of large size, thousands of blocks each containing from 100 to 300 cubic feet being exposed on the surface of the principal moraine. In the period of its greatest extension the ice apparently passed over the ridge of the cape as far east as Orleans, crossed the valley of Nantucket Sound, and deposited on the island of Nantucket the slight morainal masses which there exist, and which perhaps mark the extreme advance of the ice on this part of the coast.

North of Orleans and thence to the end of the cape there is no distinct morainal accumulation, but occasional wide heaps of drift and the clogging of the pre-Glacial valleys show that the surface was traversed by the streams pouring forth from the glacier. The general lack of erratics other than those which may have been ice rafted, or of any accumulation which can be classed as a moraine, or even as distinct till, shows that at this point the glacier, if it actually lay on the surface, was probably so weak and thin that it had no longer any considerable abrading or transporting capacity. The conditions here resemble those found on the southern part of the highland of Marthas Vineyard, where large portions of the surface are nearly driftless.

Although the carrying power of the ice as marked by the accumulations of erratics was not great, that of the streams which flowed from beneath the glacial sheet was excelled, so far as I have found in New England, only by those which deposited the great sand plain of Marthas Vineyard. As to the extent of the deposit, that of the cape is unexampled elsewhere in southern New England. The area is probably not less than 120 square miles, but the thickness appears to be much less than that of the like mass in the island to the south.

GLACIAL DEPOSITS.

The deposits due to the direct action of the glacial sheet are the till, the moraines, and the washed drift accumulated in the eskers and the sand plains.

The till deposits of this district are neither extensive nor characteristic. Along the north shore especially the areas are immediately underlain by the Barnstable clays. The coating is evident, but very

irregular; in places it is so thick as to resemble a morainal accumulation; at others considerable tracts appear to be quite without the deposit. Toward the eastern extremity of the cape the coating becomes thinner and less recognizable. Angular erratics are rare in the section beyond Yarmouth, and beyond Orleans few erratics greater in size than those termed by Chamberlin "bowlderets" are found, and these appear to have been conveyed by floating ice.

Between Orleans and the northern portion of Truro the till becomes a mere confused mass of the materials of the local beds over which the ice has passed in its movement, with occasional erratics of moderate size which were brought from a distance. It is difficult to recognize it as a distinct element in the sections, for it is essentially wanting over large areas of the surface.

The morainal deposits of the Cape Cod district, though less extensive than those found in the central parts of the continent, are by far the most characteristic in New England, presenting phenomena which are in many ways peculiar. They deserve, therefore, the detailed consideration that will here be given them.

The moraines of southeastern Massachusetts are singularly distributed. In southern New England they lie usually in lines which are evidently almost at right angles to the direction of the ice motion, and variations from this position can usually be explained by the topography of the bed rocks over which the ice moved; but in the cape district, including the neighboring islands and the mainland, the ridges are set at curious angles to one another. There the following directions may be noted:

On the mainland the Plymouth moraine, which extends in a general southerly direction from near the harbor of that name, appears at first sight to be the largest, and is perhaps the most continuous, deposit of the kind in New England. In its northern portion, at least in Manomet Hill, it is underlain by the Truro beds, which arrangement has given a false impression as to the depth of the glacial waste. With some interruptions it is continued southward to Monument River, at the base of the cape, in an approximately meridional axis as far as Woods Hole, and thence, deflecting westward about 30°, it is continued down the Elizabeth Islands nearly to their southern extremity.

On Marthas Vineyard there are two evident morainal belts parallel to that of Falmouth—one on the north side of the island, which is characteristically developed; the other in the central section, which is faintly shown, but can be traced by scattered patches of bowlders. On Nantucket there is a small area of moraine on what is known as Sauls Hills, but the axis of the accumulation is not well indicated; it appears to be in a general east-west direction.

On Cape Cod, occupying, as before noted, the high land formed by the ancient divide of the tilted series of beds, there is a morainal mass extending in an east-west direction from Monument River to the

eastern part of the town of Brewster; it may be regarded as continued in a slight form into the western part of Orleans. It is to be observed that this ridge lies at nearly a right angle to the course of the Falmouth moraine, with which it, in effect, coalesces at its western end. Although the general direction of this moraine is east and west, its shape is somewhat concentric, the curve being toward the south, the most southerly part thereof being near Bass River. It is thus evident that there are two distinct alignments of ice-morainal ridges in this district; the one, that which is clearest in its direction, being meridional in the Plymouth ridge, but deflected to a northeast-southwest course in its more southern elements; the other having essentially an east-west course.

So far the diverse positions of the moraines in the Cape Cod district have been explained by the theory of lobations in the front of the glacier, portions of the ice sheet pushing out in broad tongues, each of which made its frontal wall. These walls formed successively, intersecting one another in much the same manner as that of Falmouth intersects that of the cape. While in nowise doubting the adequacy of this explanation as applied to the interior districts of this country by Chamberlain and others, I am compelled to question its applicability to the field now under consideration, for the following reasons:

The Cape Cod district comprises no strong topographical features which could have caused the ice sheet to flow in the directions which would have to be postulated if these several moraines were formed at right angles to the axis of movement. It is unreasonable to suppose that, while the general course of the ice in the neighboring interior district was from northwest to southeast, it should have been directly southward in Massachusetts and Cape Cod bays and directly to the east in the region about Plymouth. On the contrary, the natural conditions, so far as they can be ascertained, would have led the ice in these bays to flow eastward toward the open sea and not southward toward the high ridge of the cape. I have therefore been compelled to seek another explanation of the axial order of these moraines, and have framed what seems a plausible hypothesis to account for this order without having recourse to the theory of lobation of the ice front, which has its difficulties, as just noted. This hypothesis is, in effect, that the moraines of the Cape Cod district are not of the ordinary type, but belong to a hitherto unrecognized group of hilltop drift accumulations, which, though essentially morainal in their nature, were formed under peculiar conditions, rendering them of slight value as indices of the direction of the ice movement.

It has already been incidentally noted that certain parts of the several moraines described in this report rest upon antecedently formed ridges, which, in effect, were the ancient drainage divides of the country. Let us now examine the several deposits to determine how far this peculiar character is possessed by the moraines in general. Begin-

ning with the northernmost of these ridges, Manomet Hill, in Plymouth, it will be found that the elevation is composed mainly of stratified sands, apparently of the Truro series, as has been recently shown by the excavations made in lowering the grade of the State road, which traverses the northern end of the ridge. In other words, the mass of the ridge is of pre-Glacial age, and was probably a divide between the headwaters of the Buzzards Bay river and that which drained the basin of Cape Cod Bay. So far as can be ascertained, the same underlay of sands extends beneath the rather indistinct morainal ridge that continues the Manomet Hill deposit southward to the base of the cape. These sands are not clearly seen, in sections, to pass beneath the morainal belt, but are exposed near by in positions which make it tolerably certain that they must underlie it in the manner of a pedestal, as in the case farther north. (See fig. 92.)

The Falmouth continuation of the Plymouth ridge is by far the longest and most united mass of morainal material yet noted in New England. It extends from Monument River to Woods Hole without any breach in its distinct wall, which rises to a height of from 100 to 200 feet above the sea level throughout its length of about 18 miles.

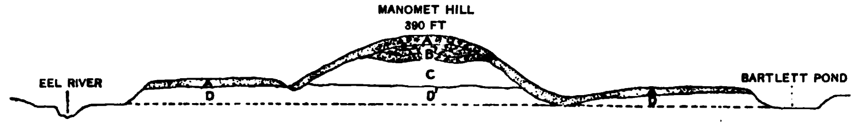


FIG. 92.—Diagrammatic section of Manomet Hill, Plymouth. A, glacial deposits; B, observed Truro deposits, 100 feet; C, supposed Truro deposits, 150 feet; D, sands and clays of unknown age, 100 feet; D', supposed continuation of D beneath the hill.

As this belt is but little traversed by roads which have been at all graded, and as its surface is covered by a dense tangle of scrubby vegetation, it is not easy to obtain sections which reveal the nature of the underlay. At Woods Hole and thence northward for about 4 miles there is abundant evidence that the moraine rests upon a ridge of older deposits. On the western face, nearly as far north as Gunning Point, the underlying clays of the older series can be traced, rising from the shore to the height of from 60 to 80 feet. Here and there along the main highway which skirts the shore to Monument River the conditions of the soil and the level of the streams also indicate that the same ridge of older rocks persists beneath the morainal cap, attaining perhaps at some points between the valleys of the brooks a height of more than 100 feet above the level of the tide. On the east side of the ridge the streams and lakes show by their levels that the ridge continues on that side of the moraine. The facts justify the conclusion that the greater part of this morainal ridge rests on the summit of a pre-Glacial divide which separated the waters of the old Buzzards Bay river from that which formed the valley that is now Vineyard Sound.

With a change of direction from north-south to northeast-southwest the Falmouth moraine is continued southward in the Elizabeth

Islands. In these isles the erratic material is in all cases but a thin overlay resting upon the crest of an ancient ridge cut in the Naushon sands, which are considered the equivalent of the Truro series. At no point, so far as I have observed, does the moraine appear to be more than 25 feet thick. In all the observed localities it evidently rests on the top of a divide formed before the advent of the ice, and it is lacking over large areas, where the stratified sands appear with only occasional bowlders resting upon the surface. Of the mass of material composing the Elizabeth Islands above the plane of the sea, certainly not a tenth, and perhaps not a twentieth, part is of morainal nature. The rest may be of glacial origin, but if so, it was deposited far in advance of the ice and long before the advent of the glacier in this part of the field.

On Marthas Vineyard the main or northern moraine appears at first sight—and even after some inspection—to be made up of bowldery material, but on careful investigation I have found that it is a pre-Glacial ridge, the pedestal being formed of a stream divide cut in the Cretaceous and Tertiary strata. On account of the misleading appearance of the ground, I was led, in my report on this island,[1] much to overestimate the depth of this glacial wall. It has not half the mass stated in that report. It is doubtful if the average depth of the deposit exceeds 40 feet. The ridge occupied by the moraine is not completely covered with the deposit. For considerable distances the top of the elevation is essentially without materials which, from their character or distribution, may be classed as truly morainal. At other points, especially in the middle portion of the belt, on the estate known as "Seven Gates," the deposit constitutes a very characteristic morainal belt, with numerous large kettle holes and with bowlders in such abundance that the masses appear like ruined cyclopean masonry. The southernmost moraine of the island also occupies the summit of a divide, but the erratic element is small in amount and only here and there assumes a morainal character.

In the territory between the two moraines of Marthas Vineyard there are, as before noted, many fields which are so far free from glacial waste that they may fairly be termed driftless. It is not easy to find any material on them that may be classed even as till. Rarely is there a foot, in depth, of this deposit. This driftless character of surface is so complete that the plowshare will turn up Tertiary or Cretaceous beds containing no trace of erratics. Fields of this driftless soil some acres in extent lie within 2,000 feet of the wall-front moraines. On the north side of the principal moraine the same phenomenon of nearly driftless fields is observable, but in a less distinct manner. The areas without erratics are small, and those which are quite without till are at no point, so far as I have observed, more than an acre or two in extent. They occur at the foot of the slope on which the moraine lies, usually

[1] Seventh Ann. Rept. U. S. Geol. Survey, 1886, p. 312.

quite near the sea level. This feature of small driftless areas over which the morainal matter must have passed on its way to the glacial front indicates that the conditions which determined the deposition of the detritus were peculiar.

There is another peculiarity of the Marthas Vineyard moraines which appears to throw some light on the conditions of their formation. While commonly the ridge of detrital material is placed on the very crest of a divide, adding distinctly to its height, it not infrequently is deposited as a sheet on the southerly or outer face (outer in relation to the glacial movement) of the ridge on which it was formed. The effect is as if the materials had been pushed up the northern slope and had fallen into the attitude in which they are found.

In the case of the Cape Cod moraine the evidence is sufficient to show that the mass occupies the considerably elevated surface of a ridge which was formed before the advent of the ice. This ridge continues with no complete interruption from the base of the cape to Orleans, except for the rather deep and wide break at Bass River. So far as I have been able to determine, the moraine is gathered mainly on the southern side of this ancient divide, though it generally rises somewhat above the crest line. The feature noted on Marthas Vineyard, of considerable areas of the more ancient deposits without glacial waste, is noticeable to the north of this moraine, but is less extensively developed than on that island.

On Nantucket the moraine appears to crown the summit of an elevation composed of the Saukaty beds, which probably belong to a time immediately preceding the deposition of the Nashaquitsa series. The conditions are not clearly indicated, but there is little reason to doubt that this relatively unimportant accumulation is placed as are the others above noted.

The facts above described warrant the statement that all the characteristic morainal accumulations of this district are placed in singularly close relations to the crests of ridges which existed before the ice sheet invaded this district. The few apparent exceptions prove on examination really to be not such. Of these the most striking is the case of the northern moraine of Marthas Vineyard, where the bowldery deposit descends into a valley about the headwaters of Witch Brook. In this relatively low place, which still is about 70 feet above the sea, the moraine becomes somewhat scattered. It is, in effect, a rather flat, very stony field, in place of the well-defined accumulation exhibited on the higher ground on either side. So, too, the same morainal, detached hills which lie here and there on the north slope of Cape Cod and Marthas Vineyard appear on inspection to be small elevations of the Barnstable series, which bear some coarse drift or else masses dropped from a stranded iceberg.

The relations of the moraines in this district can not be explained on the supposition that these deposits are revealed only on the highlands,

being elsewhere covered by later accumulations of washed sands. This suggestion would not be entertained for a moment by any student of the district who approached the problem without a decided preconception; although, as I know from experience in making the examination, it requires rather careful observation to avoid the mistake of supposing that the whole mass of these several ridges is of a morainal nature.

So far as I am aware, none of the moraines of the central and western portions of the country are placed on the crests of divides in the manner shown to be the rule in this shore-land district; nor am I aware that any of the accumulations in the interior parts of New England occupy the crests of ridges, except when their bases may accidentally coincide with those elevations. It therefore may be fairly assumed that there has been some peculiarity in the condition of the glacier in this part of the country which has served to bring about the curious result. I have not been able to determine the precise cause of this occupation of the preexisting divides by glaciers, but the possible explanations appear to be but two, and these will be briefly stated.

The first hypothesis is that the ridges may have served in forming a moraine by arresting the flow of the ice, already languid in its movement, for the reason that it had become attenuated at its margin. Hanging on these crests its front may have been retained in one position for a considerable time, which permitted the accumulation of the morainal deposit. The difficulty with this view is that it does not explain the absence of drift in the fields near the well-developed morainal lines. The second hypothesis is that, the region being depressed beneath the sea to a considerable but unknown depth, the ice, while remaining as a united sheet, may have floated over the valleys, grounding only upon the ridges and there depositing its contents of rock material. The portion of the ice which was shoved over the crest was probably broken into fragments which floated away. This hypothesis will explain the absence of till on much of the lowlands where, had the ice rested on the surface while it melted, it should remain to mark the decay of the sheet.

The hypothesis of the partial floating of the attenuated ice sheet finds a certain amount of support in the evidence which goes to show a considerable subsidence during the period of formation of the sand plain in front of the moraines. As I have elsewhere shown, these plains were certainly formed under water while the land lay at least 100 feet lower than its present level, and the actual depth of the submergence may have been much greater than the minimum required for the construction of the plains. The hypothesis will perhaps serve to explain also the departure of the Cape Cod moraine from the normal direction. As before remarked, it is very difficult to see how a glacier moving under ordinary conditions would have a path parallel to the shore; but if the sheet be conceived as floating in the sea, though its

course might be generally eastward, its margin might be pressed continuously or from time to time against the submerged ridge on the south, on which would be dropped, as the ice sheet shattered or broke up into bergs, a portion of the contained débris. The main objection to this hypothesis is that evidence as to the actual floating of the ice over the valleys is lacking; yet it demands only conditions which must exist wherever a glacial sheet enters the sea, pushing out into water so deep that the mass leaves the lower-lying parts of the bottom. Somewhat in its favor is the fact that over the nearly driftless fields near the Marthas Vineyard moraine occasional large solitary erratics are found, and sometimes heaps of coarse débris in positions which suggest that the materials have fallen from the base of a floating glacier or from an iceberg.

It must be confessed that both hypotheses present serious difficulties; but in view of all the facts, the one last stated is more satisfactory than that of marginal lobes producing interlocking moraines—a hypothesis which does not seem applicable to this field.

RELATIVE AGE OF THE MORAINES.

The relative age of the moraines in this district affords an interesting field for inquiry. The only criterion which appears to be accessible is that which may be derived from the comparative amount of decay of rocks of apparently the same measure of resistance to such change. Judged by this test, the moraine of Cape Cod is to be regarded as rather newer than that on Marthas Vineyard; the bowlders of like petrographical species are less broken up, and interstitial decay has penetrated to a much less depth. These determinations are based on mere inspection, but the impression thus obtained by many successive visits to each field at short intervals is clear.

Much evidence as to the petrographical nature of the hidden rocks of southeastern Massachusetts and the neighboring sea bottom can doubtless be obtained from a careful study of the materials in these moraines. This task has not been formally undertaken in the preparation of this report, but incidentally certain points have been noted, of which only one need be mentioned here, viz: On Marthas Vineyard the drift abounds, in a remarkable manner, in masses of chalcedony, some of which are a foot or more in diameter. The pebbles are so numerous that many tons could be gathered on a mile of beach on the north shore of the island. This material is not found on the mainland, nor is it known on the moraine of Cape Cod. It is therefore probable that it was riven from the area now covered by the sea.

CLAY BOWLDERS IN TILL.

The till of Cape Cod, especially where it occurs in the moraines, or has a morainal aspect, occasionally contains large masses of clay which evidently were brought to their resting places in the manner of other

erratics. These masses can be found scantily at several places on the cape. They were most clearly shown in an artificial escarpment which for some years existed near the steamboat wharf at Woods Hole, the site of which is now occupied by the Nobska House. In the excavation of a low drumloid hill which existed at the place just mentioned, a dozen or more of these clay bowlders, varying in diameter from a few inches to 6 feet, were noted by me in the course of three or four visits to the locality. Traces of the same bowlders have been seen on the northern slope of the cape and in the district about "Quisset" Harbor. As such bowlders have not been found on Marthas Vineyard in the numerous sections of similar drift materials, it is desirable to seek an explanation of the peculiar limitation of their occurrence. These conditions seem to have been as follows:

The clay of which these bowlders was formed was of a tenacious, uniform quality. Although much oxidized, it was seen to be of the same general character as that found in the brick-clay pits of the region about North Barnstable. That the clay was rather soft when it was moved is indicated by the fact that the surfaces of the masses were crowded with pebbles, in the manner in which lumps of clay, made by the waves on the seashore from the waste of clay cliffs, are coated with a layer of pebbles which have been pressed into the mass. As the glacier evidently slipped over the surface of such clays wherever that surface was of a continuously sloping form, as it now is on the northern versant of the cape, it seems likely that these bowlders were riven from areas where the ground was cut into deep ravines after the manner of the so-called bad-land topography—conditions which would favor the formation of erratics. That such irregularities existed in the cape area is sufficiently shown by the irregular "noses" or projections of clay—the so-called clay "pounds" which have been dug into here and there to obtain materials for bettering the sand roads of the district. So far as I am aware, clay bowlders as large as those at Woods Hole have not been found in other regions. Their rare occurrence is perhaps attributable in part to the fact that a deeply indented topography, formed in soft clays, has rarely been so eroded by an ice sheet. (See Pl. XCIX.)

LENTICULAR HILLS.

The class of drift deposits known as lenticular hills or drumlins is practically wanting in the southeastern portion of Massachusetts. There are no instances in which elongated arches of till are sufficiently well developed to merit a place in this group. Here and there, however, are morainal hills which show distinct traces of the action which gives rise to these regular forms. The ridges north of Woods Hole, between that village and Quamquisset Harbor, closely approach in shape what would be termed drumlins of the lowest order if they lay in the central part of Massachusetts. So, too, on the north side of the

cape, some of the drift hills in the town of Bourne show traces of a like regularity of outline. On Marthas Vineyard several of the morainal ridges in West Tisbury and Chilmark, especially that known as Prospect Hill, are distinctly of a drumloid form.

The arched hills of the cape district are, so far as I have observed, limited to the higher ground, and they approach more closely a symmetrical form as the altitude above sea level increases. This is not the case in the more northern parts of the coast of Massachusetts, for about Boston Harbor and in Ipswich very perfect specimens of the type are formed rising from the sea level. In any discussion as to the origin of these curious topographical forms this peculiarity of their distribution must be considered.

It is noteworthy that in this district the drift hills are more shapely on the side against which the ice moved than on that which was turned away from the stream, and also that the ridges of the pre-Glacial topography cut in the sands, gravels, and clays of the Cretaceous, Miocene, and Pleistocene formations have been in many cases rounded into drumloid forms. This is particularly the case on the western side of Marthas Vineyard, though instances of the same nature exist on the central and western parts of Cape Cod. Some of the hills near the Chatham Harbor margin of the Truro beds have a distinctly drumloid outline. (See Pl. XCIX.) These facts clearly point to the conclusion that whatever may have been the cause which led to the local deposition of the deep sections of till composing characteristic drumlins, the final shaping of these forms was due to the action of the ice as it passed over them.

WASHED DRIFT.

In this field, as elsewhere in New England, the washed drift may be divided into three tolerably distinguishable groups: eskers (nearly absent here), pitted plains or kames (rare), and sand plains or morainal aprons. It is to be noted that the materials composing these deposits differ less from those of the ordinary till than is usual in the more northern parts of Massachusetts. Here the till itself is always very sandy, its pebbles are much rounded, and the clay element, as compared with the more northern localities, is relatively small in quantity. This feature is probably due to the diminished cutting power of the glacier on its outer margin and to the extent to which its detritus was worked over by the water which flowed beneath the ice on its way to the front of the sheet. The result of these actions was to diminish the total amount of the till and to make the remaining portion much sandier here than elsewhere. As a consequence of this, it is often difficult to distinguish between the drift which has been deposited in water and that which has been left upon the surface by the melting of the ice in which it was contained.

One of the eminent peculiarities of this district is the general absence

of eskers. So far I have not been able to find any characteristic examples of these structures on Cape Cod. In the region from Bass River to Orleans there are certain ridges extending in a north-south direction which may possibly belong to this group of deposits, but I suspect that they are the remains of the ancient topography cut in sands of the Truro series. I am the more inclined to this view for the reason that the one ridge on Marthas Vineyard which I identified in my report on that island as an esker has since been proved by a section to be an old pre-Glacial feature, slightly modified by a coating of washed drift or very sandy till.

The probable absence in this field of eskers of the molds of the caverns in which flowed the subglacial streams goes to support the hypothesis that the ice in this section did not generally rest upon the surface, but came in contact with it only on the higher parts of the ground. Thus floating, there would be no chance for the development of the ice-roofed channels, the shapes of which became elsewhere molded in the débris with which they were in time filled. As these eskers descend to the level of the sea in the district about Boston, and are found in the region north of a line stretching from Boston to Narragansett Bay, it may, perhaps, be inferred that the conditions which are indicated in the Cape Cod district were of a rather local nature.

Pitted plains of the type so common in the districts where eskers exist are not often found on Cape Cod or in the islands to the south. The only good examples are on the frontal apron south of the moraine, where ice remnants, icebergs, or ground ice left by the retreating glacier appear to have been partly buried in rapidly accumulating sands, leaving where they melted depressions to indicate the positions they occupied. A trace of the same action is found in the central part of the great plains of Marthas Vineyard, where the occurrence of a small lake with steep sides can be accounted for only on the supposition that its site marks the place where a stranded iceberg was buried in the accumulation of sands which constitute the mass of the morainal apron.

An ordinary type of kame deposits, consisting of a number of hillocks of arched form huddled together quite without definite arrangement, a type very common in the town of Plymouth, appears to be lacking in the cape and islands. This peculiar local topography of the washed drift can most readily be explained by supposing that when the ice came to the point where it ceased to rest in the bed rock and began to float, its under surface would for a time retain the form impressed upon it by the contours of the surface over which it had flowed. There would thus come to be a space between the base of the rotting ice and the sea bottom into which the débris coming from the land would naturally be crowded. If the ice had much movement the resulting shapes of the drift would of course be destroyed, but at a late stage in the retreat of the glacier its stagnation might be so far complete as to leave the molded sands and gravels as we find them. The occurrence of this

remarkable kame topography on the mainland and its absence on the neighboring peninsula and islands is what we should expect on the hypothesis that the ice was in part afloat in this portion of the field it occupied.

The characteristic form of washed drift occurring on Cape Cod and the neighboring islands is the deposit of sand and gravel laid down in front of the moraines. These deposits are more extensive in this district than in any other known to me except, perhaps, on Long Island, New York. It is to be noted that these great morainal aprons differ in certain ways from the sand plains of the mainland. On that field the plains are in most cases at the end of distinct eskers, and clearly mark the places where a subglacial stream passed into the open air or open water. They are rarely, if ever, distinctly related to the axis of defined morainal ridges, though we often find bowldery tracts at about the point where the esker passes into the plain. In these morainal aprons of the cape district, on the contrary, there are no eskers leading to them, but the broad field of sand extends up to or near the wall of coarse débris. Next this wall there is commonly a shallow, wide depression, from which the apron rises to a point somewhere about a mile away, whence it declines to the sea. Such is the form of the great plains of Marthas Vineyard and Nantucket. In Cape Cod the depression or ditch is less distinct; it will, however, be remarked by an observer who has noted the feature elsewhere.

While the ordinary sand plains have their "feeding" eskers—molds of the channels through which the débris came—those that front the great moraines of the cape lack these features. Here and there are breaches or low places in the morainal walls through which currents of water appear to have flowed, as is shown by the signs of erosion in the channels in front of these breaches. The plain exhibits broad, irregular channels which lead down to the sea. These scour ways do not appear to have been at any time occupied by open-air streams, but rather to have been excavated on a water-covered surface. This feature, like the ditch in front of the moraine, is less distinct in Cape Cod than on the neighboring islands, yet it is disclosed to close inspection and partly indicated on the topographical map. In reports on the geology of Marthas Vineyard [1] and on the geology of Nantucket [2] I have given in some detail an account of the characteristics of the plains that lie in front of the moraines on those islands. The like deposit on Cape Cod differs from those noted in the papers referred to in that it is ruder in form, that it has numerous considerable lakes on its surface, and that the scour ways are generally occupied by brooks.

The peculiarities of the morainal apron on Cape Cod, taken along with the evidence of beds of clay apparently belonging to the Barnstable series, lead to the conclusion that in place of the very deep deposit

[1] Seventh Ann. Rept., U. S. Geol. Survey, 1885-86, p. 316.
[2] Bull. U. S. Geol. Survey No. 53, 1889, p. 19.

of sand which exists beneath the plain on the above-named islands we have a relatively thin layer of detritus imposed upon a preexisting topography which is cut in rather impervious beds. The numerous swamps and lakes, as before remarked, so high above the sea that their waters could not be retained by sand barriers, are probably to be in part accounted for by the supposition that they lie in valleys which originally drained northward, as appears to have been the case with nearly or quite all of the pre-Glacial streams of the cape. These streams were dammed by the moraine. In perhaps larger measure, however, these basins are to be regarded as the molds of ice remnants about which the washed sands were gathered. That such was the case is shown by the fact that the sides of the depressions are usually very steep, the detritus having slopes which it could not have assumed at the time of its deposition unless there had been some barrier, such as the walls of ice would have supplied, to keep it from being conveyed into the cavity.

The contours of the great plains of Cape Cod, like those on the islands, clearly indicate that the material was deposited under water. In aerial overwash plains, formed as detrital cones, we find necessarily a continuous down-sloping surface. In these plains in front of the glacier of southeastern Massachusetts the surface has the gently rolling character characteristic of sands that have been arranged on the bottom of a sea which was the seat of tolerably strong currents. The slope of the Cape Cod morainal apron is essentially the same as that of the similar structures in this district, the rate of the decline to the seaward being from 12 to 15 feet to the mile.

The surface of the plain of Cape Cod is prevailingly composed of rather fine, siliceous sand. This material forms a bed having a rather remarkably even thickness of from a foot to 18 inches. This usually passes downward by a rather sharp transition into a pebbly layer in which the pebbles are from the smallest sizes up to that of a cricket ball, though rarely so large. At greater depths the admixture of sand and pebbles is rather uniform, the mass having obscure stratification. Now and then a bowlder is found. These bowlders are almost always rounded and rarely exceed 2 feet in diameter; they are often found in groups associated with gravel, and they occasionally occur on the surface. Such stratification as is exhibited is not distinctly cross bedded. In these, as in most other features, except the presence of numerous lakes, the cape plain in no way differs from the like structures in the other parts of the district.

In considering the origin of these morainal aprons of southeastern New England, the fact should be noted that deposits of like nature do not, so far as I am aware, exist in front of the moraines in the interior of the country. There are there, it is true, traces of overwash plains, but they are always much less continuous; they have, in a word, more of the nature of detrital cones. Those I have seen in Ohio, Michigan,

and Wisconsin also lack the depression next the moraine, the pits occupied by lakes such as occur on Cape Cod, and the scattered bowlders in the mass and on the surface of the deposit. The difference between the structure in the two districts probably arises from the fact that those in southeastern Massachusetts were formed under water, while those in the west were deposited mainly in the air. If we suppose that the sea extended up to the ice front, and that the finer materials were, at the time of melting, given into the control of tidal currents, we can well conceive that the part of the débris which could be thus transported would receive a wide distribution over the neighboring bottom; the floating ice would convey many bowlders from the front of the moraine, dropping them haphazard as they melted; the tidal currents would carve channels on the bottom as they cut them on any sands over which they may flow. In a word, the assemblage of conditions exhibited in the morainal aprons is more consistent with the supposition that they were formed on the sea floor than in any other manner.

It will be noted that a number of the peculiar features of these moraines together tend to show that this district was rather deeply submerged at the time of their formation. I have, as yet, been able to find no evidence going to show whether the submergence was so deep as to cover the tops of the morainal walls. It may be noted, however, that on Marthas Vineyard the portion of the moraine which faces on Tisbury River has no apron on its front, but rather a steep overwash plain or long detrital cone which terminates in a valley that may have carried the wash from the glacier down to the neighboring great apron. It thus seems probable that this portion of the morainal front lay above the level at which the sea was placed at the time it was formed.

OUTER LIMITS OF THE CAPE COD ICE SHEETS.

In view of the fact that the ice sheet on this portion of the Atlantic coast was evidently thin, the question arises as to its probable extension beyond the limits to which it can be traced by the remains it has left upon the land. On Cape Cod we find in the Truro-Wellfleet district very slight evidence—if it be, indeed, evidence at all—that the ice lay upon the surface. I am quite prepared to believe that the drift in this area is due to the action of floating ice dropping the waste it carried upon the bottom. We may from the evidence fairly conclude that we are here near the eastward margin of the effective ice sheet.

On the south the extension of the glacier appears to have been to a relatively farther point than in the east. On Nantucket there is a small area of low but fairly characteristic moraine with a well-developed frontal apron. On the island of No Mans Land, south of Gay Head, we have an extensive deposit of a till-like nature, which may, however, be due to floating ice. On the southernmost of the Elizabeth Islands the glacial drift, though scanty in amount, is still sufficient to attest the presence of the ice in that part of the field. It thus appears that

the glacier probably extended its action over all the district of Cape Cod, though on the extreme south and east the effects which it exercised may have been due to portions of the ice which had been broken from the united mass and which were floating in the open sea. It is hardly to be supposed that a sheet so thin as the glacier was in this part of its course could have held together for any considerable distance from the shallows, capes, and islands where we last trace it.

In closing this portion of the report attention may be called to the value of the information concerning the frontal condition of the glacier which southeastern Massachusetts affords. In no other section of the country are the data for inquiry so ample—and, it must be confessed, so difficult to interpret.

POST-GLACIAL DEPOSITS.

This group of deposits includes the spits, hooks, and beaches, the dunes, the marine marshes, the fresh-water swamps, the soil, and, finally, the sea shoals.

One of the first-named group of constructions we have in the hook which constitutes the whole of the area of the town of Provincetown, one of the finest existing examples of such forms. There is certainly none other of its kind in this country which so well deserves attention. The history of this feature appears to have been in general as follows:

When, after the disturbances of level which attended the last Glacial epoch, the land of Cape Cod came to its present apparently stable attitude, the elevated country of Truro extended somewhat farther to the north and east than it does at present. As this last portion of the cape in the east was worn down by waves and currents in the manner in which the work is now going on, the débris was, in part at least, carried to the end of the land, there beginning the growth to the northward of the spit. As noted by Prof. W. M. Davis, the sea beach at the north end of the Truro highland marks the point where the encroachment of the sea was arrested by the beginning of the accumulation of sands which has extended to the village of Provincetown. (See Pl. CII.)

It seems likely that there was shoal water where this spit was formed; before it began to form, indeed, the erosion of the northern face of Truro, which has just been noted, may have been part of a considerable wearing that had gone on before the spit had begun to form. There is a bit of evidence on this point drawn from the results of the "driven" wells sunk in the sand at Provincetown which, though not certain, has some value on this point. These wells, which were sunk to a depth of a few feet below the level of the sea, in place of yielding the very pure water which elsewhere has been obtained from such spits, have afforded a quality which, on account of the large amount of iron it contains, is hardly fit for use. Water of the same

nature is characteristic of the old sands of pre-Glacial age wherever they have been tapped in this part of Massachusetts, the defect being due to the complete oxidation of the considerable amounts of iron which they contain, and perhaps to other chemical changes, such as do not occur in the clear siliceous sand of which the spits and beaches of this region are made. It therefore seems probable that the water of the Provincetown wells is drawn, not from the beach sands, but from the lower-lying pre-Glacial deposits.

The process of growth of the Provincetown hook appears to have been mainly by successive beaches, each formed in front of the next preceding, and each projecting northward somewhat beyond its predecessor. The supply of sand seems to have come, in part at least, from the wearing of the coast line of the Truro-Wellfleet district, and in part from the sea bottom to the eastward. There has evidently been a balance of actions which of late has served to urge the sand to the northward toward the present end of the cape. It is evident that for a time no distinct hook existed in the end of this spit; its form was somewhat like that of Monomoy, but, probably for the reason that the water deepened beyond the shallow on which it at first grew, the end near its present stage of growth turned westward to form the hook with which it now terminates.

At first the Provincetown spit was evidently narrower than it is at present, but with the carriage of sands northward along the shore the water on the side of the open sea was shallowed by the formation of a broad shelf which enabled a succession of beaches to form, each somewhat farther out than its predecessor, and in this manner the spit has been considerably widened. This process of growth appears not to be continuous. From time to time, with the varying direction and energy of the waves and of the currents which they induce, the beach works in, again to be built out with the resumption of the carriage of waste from the shore southward.

Along with the carriage of sand by the sea there has gone a considerable movement of materials by the wind. This has taken place mainly in a westerly direction from the outside beaches. When the tide is out and the air dry, even a moderate wind will move the finer parts of the material almost as easily as though it were snow, and in great storms quartz pebbles up to the size of peas may be observed to fly along at the height of some feet above the earth. As the wind loses a part of its speed in passing over the surface of the ground, the particles of sand and gravel which it bears soon fall into the eddies of the current, there forming the beginnings of dunes. As soon as these dunes form they begin to march before the wind; the bits slip up the exposed side and pass over the crest into the sheltered sea, where they remain at rest until the whole mass has been shifted forward in the same manner. In this way, by the process of constantly moving the windward layer to the leeward side, the dune slowly marches inland.

Various influences tend temporarily to arrest the march of these Provincetown dunes, as they do all such masses of wind-blown sand. As the bits journey they decay, so that they naturally cement together. Moreover, certain species of plants, such as the beach grasses, have developed the capacity to grow in the arid soil of these ridges. This they do so effectively that their roots and leaves make a mat which deprives the wind of access to the heaps.

In the present state of the Provincetown spit hook the structure appears, as a whole, to be in a tolerably balanced state, a condition into which such structures are apt to come at a certain stage of their growth. The cape does not appear to be extending northward, unless it be very slowly, the tidal currents from the bay interfering with this growth. The hooked extremity, which is made up of detritus that washed around the end of the cape, does not appear to have gained in extent in a material way during this century. The only change which menaces the established order of this unstable new land is the present inward movement of the beach on the eastern side, near Moon Pond. There we have a well-recognized danger that the sea may break through, with the result that the valuable harbor of Provincetown would be endangered. It certainly would become shallower, and it might be so far changed as to lose its present great importance as a port of refuge.

The erosion of the sea on the eastern face of the cape from the northern end of Truro to the central part of Eastham has provided not only the sand which has gone to construct the Provincetown area, but also that which, moving to the southward, has built the large and beautiful line of barrier sand beaches that extends from opposite Chatham Center to the end of Monomoy Island. Although this isle is at present separated from the mainland of the cape by a shallow water way, it is, in its structure, a spit of the same general character as that at Provincetown, only less far developed. Already at its southern end it has begun to form the hook, which is the appropriate finish of such spits.

The amounts of débris which have gone both ways from the erosion district of the eastern face of Cape Cod appear to be nearly equal. The reason why the Provincetown spit is so much longer than that of Monomoy is, that the greater part of the sand which moved southward has been used in constructing the extensive barrier beaches that lie on the sea side of Orleans and Chatham; for these long and broad walls of sand probably contain rather more material than is held in the much more conspicuous spit hook at Provincetown. At present the Monomoy spit appears to be growing more rapidly than its northern equivalent, so that in time these two geographical growths may become even more alike than they are at present.

On the northern shore of Cape Cod, although there are no parts of the shore which are undergoing erosion, there is an interesting system of barrier beaches, which has been constructed since the land assumed

its present level in relation to the sea. The material for these beaches has evidently been derived from the shallow bottom of the adjacent bay, it being dragged in to the shore by the action of the waves. It will be observed that while on the eastern and southern sides of the cape these beaches are always drawn near the shore, so that the lagoon they shut in is quite narrow, those on the western and northern shores depart widely from the coast, so that they inclose broad fields of water, such as Wellfleet Bay now presents or such as were found at Barnstable before the harbor was narrowed by the extensive growth of marine marshes. The reason for this more remote position of the barrier beaches in relation to the shores is, that the water on the north side of the cape appears to have been, in the beginning of the present conditions, as it is at present, shallower and with a more gently declining bottom than it had on the south. In fact, the old river basin, which is now Cape Cod Bay, had evidently a much more gradual slope than had the neighboring basins on the south. Thus the ancient form of the basin has served to qualify the shapes of the existing shores.

On the southern side of the cape the evidence of coastal erosion is somewhat the same as it is on the eastern part of the area. In certain places along this shore there are evidences of considerable but variable localized coastal erosion, the waste from which is distributed along the shore and accumulated in slight barrier beaches and hooks. Of these the most interesting is that known as Point Gammon, at the mouth of Lewis Bay. At certain places, as, for instance, at Chatham lights, observations show that for a number of years the recession of the shore went on in a singularly rapid manner, at the rate, it is said, of 10 feet per annum. It is evident, however, that this was a local adjustment of the shore, caused, it is now asserted, by the development of the beach which extends to Point Gammon, and the consequent change in the distribution of the wave action. The amount of erosion on this southern shore has probably been but a fraction of that which has gone from the eastern face of the cape, where, in Truro and Wellfleet, an extensive salient, probably amounting in area to not less than 30 square miles, has been cut away to afford the débris which has been distributed on the beaches, spits, and hooks on the north and south. That the erosion on the eastern face of the cape diminishes in a westerly direction is shown by the unembarrassed outlets of the streams which enter the sound along this shore. If there had been any considerable amount of erosion here, the sands therefrom would have been gathered in adherent and barrier beaches and spits, such as exist along this coast wherever the sea has been supplied with materials from which to make these constructions.

On that portion of the western face of Cape Cod which is bordered by Buzzards Bay we find but little evidence of marine erosion. There are a few very small spits, but no barrier beaches; in fact, there are few portions of the coast south of Boston which are exposed to waves of

moderate severity where the amount of work done by the sea is so small as it is here.

This glance at the shore conditions of Cape Cod shows us that only a small part of its periphery indicates any considerable amount of wasting since the land came to its present altitude. The maximum recession can not well amount to more than 3 to 4 miles. This occurred on the eastern side of the Truro-Wellfleet coast. The next most considerable loss is on the section near Hyannis. The best evidence as to the limited amount of the loss of area is afforded by the fact that the extent of the cliff shores of the area is limited; even the frail materials of the morainal aprons have not been much cut away, as is shown by the fact that their slopes are, with rare exception, prolonged down to the level of the tide. Had they been much eroded they would face the shore in steep cliffs.

Owing to a considerable local erosion which has taken place on parts of the shore of Cape Cod, there has come to be a general opinion that the peninsula is in process of rapid destruction. This view appears to be held by many well-informed residents of the peninsula. So far is this view from being true that the converse may be taken as nearer the facts. It is altogether likely that the total area of this cape country, including all the marshes, barriers, beaches, spits, and hooks that are attached thereto, is no greater than it was at the time when, by a final step of subsidence, it established its present relations of land and sea. The aggregate of this erosion is evidently much less than that which has taken place on the islands to the south.

The submarine constructions which have been made by the tidal currents in the waters about the cape are probably, in mass, much greater than are those which appear above the plane of low water. An inspection of the Coast Survey maps discloses in the soundings a curious tangle of shoals, mostly ridge like in form. As before remarked, some of these submarine elevations are probably the divides of the smaller streams which intersected the floors of the valleys at the time they were above the sea. This is clearly the case with Stone Horse Shoal, and it is most likely so with the middle ground of Vineyard Sound. Others, especially the group about the eastern entrance to Nantucket Sound and that at the north end of Muskeget Channel, are evidently due to the action of the strong and contending tidal currents which sweep through these areas of sea. It may be noted here that the absence of any signs of marine current action on the surface of the land of Cape Cod or the neighboring islands and mainland above the level of the sand plains is tolerably good evidence to show either that the Glacial submergence did not extend above that level or that, if more deeply submerged, the ice remained on the surface until the land was reelevated to about its present height.

MARSH AND SWAMP DEPOSITS.

The marine marshes of this district are of considerable extent within the limits of the cape; their area is about 11,000 acres, the greater portion lying on the north side of the isthmus, in the Barnstable and Wellfleet reentrants. On the south and west coasts they are distributed in numerous small areas along the banks of the smaller drowned valleys and in the lagoons lying between the barrier sand reefs and the shore. As compared with the similar marshes north of Boston Harbor, these of Cape Cod exhibit a much less energy of growth. Basins which there would have been occupied by completely developed deposits are here but imperfectly covered by them. The reason for this deficiency is not to be found in any change of species, for these are the same in both districts, but probably in the fact that the amount of mud swept in by the tide is here very small as compared with what it is elsewhere; the result is that the plants are ill fed and do not attain anything like the vigor of growth which they exhibit when the water at each flooding brings much nutritious material to the plant roots. Moreover, in these sandy bays the eelgrass, which is the most effective agent in preparing the shallow water to be occupied by the marsh-making growth, does not do so well on the bottoms of drifting sand as it does on those of firmer and more supporting nature, such as are found to the north.

The fresh-water swamps of Cape Cod were originally very numerous. Though by far the greater number of them have been drained for use as cranberry plantations or converted into reservoirs to flood the vines in the proper season, some areas still remain in their natural state. In its original condition this district had a larger share of swamp grounds than any other equal area in this part of New England, and the inundated fields were more evenly distributed than elsewhere.

The reason for the great development of swamps on Cape Cod is to be found in the fact that there is a clay underlay beneath the glacial sands on the greater part of the area. Thus, the plain of the morainal apron, which in the equivalent deposits of Marthas Vineyard and Nantucket, because it is of pure sand to a great depth, is almost destitute of swamp deposits (that of the first-named island being quite without swamps), is on Cape Cod beset with lakes and with swamps which have grown in lake basins; moreover, the ridge of the old divide on which the moraine rests is wide and rather flat, which favors the development of many areas of imperfect drainage. These conditions have served to give to this region its long-continued predominance in the industry of cranberry planting. There is probably no other place where the very peculiar conditions required for this singular form of agriculture have been so well assembled.

The fresh-water swamps of this region are much better developed than are the marine marshes. The climate and soil are so dry that there is

no trace of the climbing action of the bog sponge which is so common in Maine and is still notable about Boston. This general dryness somewhat arrests the growth of the peat deposits, but it favors that of many species of bushes and some trees, such as the swamp maple and the tupelo. The result is that a large part of the peaty matter of the bogs in this district is due to the leaves and stems of phænogamous plants. On this account the bog soils are evidently more fertile than are those formed by the decay of mosses alone. It is in part to this cause that we must attribute the excellence of the cranberry plantations.

It is a noteworthy fact that a very large proportion of the lakes in the cape district have escaped the action of the swamp-making agents. Many of these basins not exceeding half a mile in diameter show no trace of peaty growth about their borders. This feature is probably due in part to the very sandy character of the shores, which makes it difficult for the mosses to become implanted there—a difficulty which is the greater for the reason that the range in the level of the water is very great. In part the hindrance arises from the considerable depth of many of these ponds and the steepness of their beaches, which makes it hard for the water lilies and rushes to take root, so that the protection which their stems afford the shore from the assault of the waves is lacking. The result is that the frail beginnings of a moss plantation are likely to be broken up long before the growth has attained the strength which would enable it to resist the action of the waves.

SOILS.

The soil of the cape differs little from that of the neighboring districts of the mainland and the islands On the north shore, from the base of the peninsula to Orleans, the general presence of the Barnstable clays or the clayey till made therefrom causes the fields to retain moisture in a way they do not in the more southern and eastern sections. On this account, rather than for any special nutritive value in the underlying material, the soil here is considerably better suited to farming than elsewhere. The vegetable matter on which the fertility of the earth so largely depends does not pass out by decay as speedily as it does in the excessively porous débris which generally underlies the surface in these fields.

Owing to the exceedingly sandy nature of the till, except, as before remarked, where it rests upon the clays of the shore, there is little difference between the soils formed on it and those formed on the sand plains lying south of the moraine; in each condition the portion of the earth which is mingled with decayed organic matter, i. e., the true soil, is rarely more than 6 inches in thickness. As the mineral matter in the drift beds of this region is exceedingly well adapted to afford the mineral elements required by vegetation, the failure of a soil to form is rather curious. The reason for the condition seems to be that the

exceedingly porous nature of the earth affects plants injuriously; in the first place by causing their roots to become very dry shortly after a rain, and in the second place by permitting the speedy and complete decomposition of the decaying organic matter, so that the earth is without the necessary amount of humus. The validity of this hypothesis is shown by the fact that wherever we find a place in which the water table is retained sufficiently near the surface to permit the tilled zone to be moistened by capillary attraction from below, there we find excellent ground for tillage; moreover, wherever the plan of plowing in green crops is followed, the results show that the soil needs only suitable treatment to give excellent returns. A considerable personal experience in tilling such soils as the sandier kinds of Cape Cod enables me to say that where they can be irrigated and where they are provided with nitrogenous matter by the inexpensive plan of plowing in crops of peas, clover, or other leguminous plants, they can be made to yield profitable crops.

It is particularly desirable to have the treatment of these soils of southeastern Massachusetts made the subject of a special and well-directed inquiry. In this district we have an aggregate area which may be safely reckoned at not less than 150,000 acres whereon all efforts at tillage have ceased. The region was once fairly well wooded, but the forests have long since been cut away and their regrowth is prevented by the numerous fires which sweep over them and which still further reduce the amount of vegetable matter in the soil. These fields, when unwooded, are sold, in the rare transfers which are effected, at from 50 cents to about $3 an acre; in their present neglected condition they are really not worth any price. In view of their nearness to rail and water transportation they should invite the attention of persons who are willing to take the pains necessary to learn the most economical methods of bringing them into tillage. Sixty years ago the swamps of this district were even more unpromising fields for agriculture than these sand plains and hills, yet at the present time, in their condition as cranberry bogs, they are worth on the average more than $100 an acre over and above the expense of bringing them under cultivation.

Of the total area of Cape Cod, only about one-eighth is so occupied by morainal matter as to be untillable; about another eighth is contained in the sand spits and beaches; so that three-fourths of the whole area is, so far as the geological conditions go, fit to be made into soil, and will doubtless in time be brought under cultivation. The morainal fields afford excellent ground for the culture of forests; several species of trees do well on this bowldery earth, among which may be mentioned the white pine and the Scotch larch, both of which grow rapidly and are free from diseases. In the occasional swamps, so placed that they can not be used for cranberry culture, the swamp cedar, which affords with a rapid growth valuable timber, may be advantageously grown.

Perhaps the only land quite unfit for profitable use is that of the washed and blown sand of the beaches and spits. In the earlier conditions of our agriculture, lands such as those of Cape Cod were not worth attention. At the present time, with the increasing use of fertilizers and irrigation, these fields are likely soon to be made productive.

The facility with which water can be stored in the elevated lakes of Cape Cod invites the use of irrigation on much of its area. From a rough eye estimate (there are no maps good enough to warrant a closer study) I judge that not far from 10,000 acres of the peninsula could be effectively watered.

HARBORS AND WATER WAYS.

In the conditions of navigation down to within sixty years of the present time the harbors of the cape were well suited to shipping. Owing, however, to the fact that these havens, with the exception of that at Provincetown, owe their basins either to flooded valleys, such as Oyster Bay, or to irregularities in the morainal fields, such as Woods Hole, they are all rather shallow and usually are shut off from the sea by bars and shoals. They are, therefore, fit only for the use of the smaller craft. Several of the ports which once sent forth many commercial ships, as, for instance, Chatham and Barnstable, do so no longer. The only port of value on the peninsula is that of Provincetown, which owes its existence to the formation of the curious beach hook which incloses its basin. The havens fit for use of pleasure boats are numerous; they are, indeed, numbered by the score. No part of the coast south of Maine so abounds in them as does the southern face of the cape. In general, these basins are susceptible of much improvement by the use of jetties, which may confine the considerable tidal water which passes through their excessively wide entrances.

More important in a general sense than the harbors of Cape Cod are the water ways which nearly traverse its width. These may be made passages by which vessels can avoid the dangerous voyage that now has to be made by all craft passing this part of the coast. A sailing vessel bound north or south of the cape has to reckon on an average of about two days' loss of time, as well as a considerable expense in the way of insurance, in making the voyage, at least during the winter half of the year. Except Cape Hatteras, there is no more dangerous portion of the Atlantic coast. The shipping which annually passes through Vineyard Sound on this voyage is said to be greater than that which traverses any like width of water in the world. From an early day there have been projects for cutting through the cape, making use of some one of the several channels—rivers so called—which nearly intersect the peninsula. Of these there are four which, with relatively slight expenditure as compared with other modern ship canals, could be opened to shipping. They are Monument River, Bass River, Town Cove in Orleans, and Pamet River in Truro.

The two last-named ways, though from an engineering point of view most practicable, are situated so far out on the cape that the worst dangers of the voyage northward would be passed before their entrances were reached; they are, therefore, not worth consideration.

The Monument River passage is, from the point of view of engineering, at least as far as opening the way is concerned, a very easy work to construct. It has, however, the peculiar disadvantage that it opens into Buzzards Bay, so that vessels must determine on passing that way from the time they start on their course around the cape. As in good weather the course can be run by a sailing vessel in twelve hours from the anchorage ground near Nobska light, in Vineyard Sound, what mariners need is a way to pass from the waters of that sound directly into Cape Cod Bay. The only passage which will afford this is that by the way of Bass River. This channel is, on the average, deeper and wider than Monument River, and it lies in a position where, at reasonable cost, vessels going northward could be provided with a safe harbor of refuge, whence, if the weather favored, they could turn the cape or could take the shorter artificial way. It is probable that the costs of these ways would not differ in any important measure. The distance from the western ports to Boston via Bass River would be longer by about 50 miles than by way of Monument River; to and from points north of Boston the additional distance would not be worth reckoning.

A considerable disadvantage of the Monument River way is that the upper part of Buzzards Bay, owing to its land-locked and currentless state, often becomes thickly packed with ice, even in winters of ordinary severity. On the other hand, the waters of Vineyard Sound, because they are the seat of strong through-running currents, are rarely thus embarrassed. It may be remarked that there is another improvement in the water ways of the cape which deserves consideration only less than a water way across the peninsula; this is, the passage through the morainal line to Woods Hole. At this point a natural breach of the moraine—one of the many which exist in the moraines of this district—affords a crooked and dangerous passage which has been much in use by vessels since the settlement of the country. A measure of benefit has been done to this way by dredging, but it remains an inadequate passage between two of the largest bays on our shore. If Monument River is to be taken as the site of the canal—and by a nearly common consent it appears to have been thus adopted—it will be more than ever necessary to provide a fit ship channel at Woods Hole, so that vessels may still have some choice as to the open route around the cape after they have entered Buzzards Bay.

Whatever is done in the way of canalizing the cape, it is clearly important that an adequate harbor of refuge should be provided on the south shore, where vessels in times of severe storm may find a safe

anchorage. At present there is no such shelter fit for the use of the larger vessels which ply along the Atlantic coast between New Bedford and Provincetown. The anchorages in Vineyard Sound, with the exception of the small havens at Woods Hole and Edgartown and the breakwater at Hyannis, are all open and exposed to grave danger from the northeastern gales. The most available of these shelters—that at Vineyard Haven—is often very much crowded, so that if the outermost ships should drag their anchors a great catastrophe would be likely to occur, in which scores of vessels might be lost. A considerable number of the shipwrecks which occur where craft are on their way around Cape Cod are due to the fact that there is no perfectly safe place in the waters of Vineyard or Nantucket sounds where they can await conditions of weather which make it fit to essay the passage.

ROAD-BUILDING MATERIALS.

The condition of the highways in Cape Cod is and always has been bad. The sandy nature of the underlay and the prevailing lack of vegetable matter in the soil make this condition inevitable unless some method of hardening the wheel way is adopted. Of these methods there are four which are more or less available at various points: The roads may be covered with oyster shells or the shells of the pecten, known locally as the scallop; they may be covered from time to time with a coating of clay; they may be graveled; and they may be macadamized.

The use of shells is in many ways to be commended where the traffic is light; but when exposed to much travel the covering is swiftly destroyed. Moreover, any general use of this material is impracticable on account of the limited sources of supply. The use of clay as a means of hardening the sands has been essayed in this district, but with poor results. The application on roads of ordinary use has to be made about once in two years, and it is so costly that in the end it is more expensive than it would be to construct a well-hardened way. Of gravel fit for road building, none is known to me except in the extreme western portion of the cape, and this is not of good quality. Thus the only satisfactory resource in this field is found in the use of broken stone, as in the well-known macadamized roads.

As there are no bed rocks attainable in the cape district which can supply material for macadamizing, it is necessary either to import the broken stone from the farther parts of Plymouth or Bristol counties or to make use of the erratics which may be had from the moraine or from the old walls composed of the smaller bowlders which have been gathered from the fields of till. As far out on the peninsula as the central part of Orleans, and within this section southward to the border of the moraine, the amount of this erratic material is great. It is, indeed, sufficient for the needs of road building in this county for all the foreseeable

future. The supply of "field stone," or those which may be had from the surface of the ground, of sizes to be used in the crusher without breaking with the sledge, is limited. It is not likely to serve for more than the needs of original construction of the roads which will have to be built within the next score of years. After that the resort will have to be the pits opened in the moraine, where usually more than half the mass excavated will be large bowlders needing to be blasted in order to be made serviceable.

The petrographical character of the morainal erratics is good. They are mostly of a granite nature, with some admixture of trappean rocks. These dike materials sensibly increase in amount as we go eastward along the moraine. In this direction we find a considerable amount of volcanic débris, mostly fragments of what seem to be indurated ash beds and breccias. As before remarked, the rock masses of this morainal accumulation are not much affected by decay. The experiments made by the Massachusetts Highway Commission in the use of the field stone on the cape—of which about 12 miles of way has already been built, a portion of it having been in use for two years or more—shows that this material is excellently well adapted to building roads. It is so slightly decayed that the amount of small fragments produced is not much greater than is needed in "surfacing" the roads. When this element is excessive an adjustment can be made by sorting the stone before crushing, the product of the softer kind being used in the lower layer of the construction.

Roads made of the bowlders found on the cape can not be expected to have the endurance to traffic that is exhibited by those which have the covering layer composed of the harder traps, such as are found in the region about Boston or in the Connecticut Valley, yet for the uses they have to serve in this district they will prove very good.

The portions of the cape which are ill supplied with road-building stones are those in the southern parts, between the western part of Mashpee and the eastern part of Chatham and the towns of Eastham, Wellfleet, Truro, and Provincetown. In the first of these districts beneath the morainal apron there are, as are shown by various ditches, extensive deposits of pebbles and bowlderets which may afford local sources of supply of stone to be used in the crusher. These should be assayed in order to avoid the great cost of hauling material from the source of supply in the moraine, which is distant and accessible only by very sandy roads. These pebbly deposits seem to lie beneath the beds of the channels which extend from the moraine to the shore. They are usually covered by a thin layer of gravelly sand. The supply for the portion of the cape beyond Orleans will have to be brought by railway from the morainal district, and fortunately the railway extending to Provincetown brings all parts of this section within an average distance of about 1 mile from transportation.

ORIGINAL EASTWARD EXTENSION OF CAPE COD.

The presence of an extensive system of drowned valleys on the Cape Cod district, including therein the islands on the south, leads to the question as to the extent to which these partly submerged lands were originally continued to the eastward. This question can not be fully answered, but some light may be thrown upon it by the facts and considerations which are noted below.

It is at a glance evident that the eastern side of the river valley into which drained the streams on the north side of the cape has been in part cut away. There is nothing to mark its former place except it be in part the shoal in which the Provincetown hook has been formed. This shoal is indistinctly continued northward, as is shown by the soundings, and the general form of the bottom of Cape Cod Bay supports the hypothesis that the valley was continued down to the depth of 100 feet or more below the present level of the sea.

On the floor of Massachusetts Bay and farther to the seaward in Georges Shoal, Cashes Ledge, and other less important elevations we have the elements of what appears to be an ancient land topography. It is possible to explain these features by the supposition that they are due to the warping of the earth or by the hypothesis that they were morainal in their nature, but neither of these views finds any definite support. Warpings of the type required to account for the facts would have to be of a type unknown in this part of the continent, at least in recent geologic periods. Moraines are contraindicated by the slight erosive power the ice evidently possessed and the thin character of the morainal accumulations on the neighboring coast.

It might seem probable that the mountain-building actions which led to the extensive dislocations of the Tertiary strata in this district were competent to bring about the formation of such ridges as we find on the sea floor in this vicinity, but the vast erosion and deposition which has taken place since these disturbances occurred would naturally have led to the destruction of any such reliefs had they been formed. Moreover, there are no indications that the stressing of these beds led to the building of sharp ridges, such as we find in these ledges and shoals. On the contrary, it is eminently probable that the region thus affected lacked at the end of the process any distinct topography except such as was given it by subaerial erosion.

It seems certain that the topography of the sea bottom in and to the east of Massachusetts Bay can not be very ancient. It evidently lies within the limits of the continental shelf—i. e., within the realm of excessive sedimentation, next the shore. Reliefs of such a sharp character would inevitably have been covered by detritus if they had long been in existence. Therefore, the probability seems to be that they are a part of the topography which, in a semisubmerged state, is preserved in the Cape Cod system of drowned valleys.

The cause of the formation of the partly or completely submerged valleys of this part of the shore may perhaps be found in the extensive dislocation which the strata have undergone in this region. If we suppose, as we well may, that the newer deposits of this part of the coast were over a large area much mountain built, the result would have been to lift what was originally a set of level and low-lying beds to a considerable height. A topography developed on such strata would be sharp, and the headwaters of the streams would be at a higher level above the sea than would be the case in the neighboring undisturbed districts. The fact that like disturbances in the region lying to the west and south have been attended by a similar preservation of the ancient topography, as in Long Island and Block Island, makes this view as to the cause of the maintenance of the Cape Cod peninsula the more probable.

In considering the conditions which have led to the formation and preservation of the Tertiary topography in the Cape Cod district, it is well to note the fact that the whole of this portion of the Atlantic coast appears to be at the present time much below the average elevation which it has recently had. This is shown by facts which indicate that the sea has not of late laid at a higher lever than about 100 feet above its present station, while the evidence from the submerged topography leads us to the conclusion that the depression below the level of most extreme elevations has amounted to at least 300 feet, and probably is much in excess of that amount. It should also be said that this submergence is not due to local causes. It is clearly a part of the very general action which has included a large portion of the shores of all the continents. The action is manifested on the eastern coast line of North America, from the mouth of the Rio Grande to the circumpolar section of the continent. It is also to be noted on the Pacific coast within the same parallels.

ABSENCE OF SHOALS IN CAPE COD BAY AND IN BUZZARDS BAY.

The absence of shoals in Cape Cod Bay and in Buzzards Bay apparently indicates a difference in the history of these basins as compared with that of the depressions of Nantucket and Vineyard sounds. The explanation may possibly be found in the fact that the sounds, in part at least, represent a region of adjacent headwaters of several streams the cols of which were in the last great subsidence lowered beneath the sea, permitting the tidal currents freely to pass through them. These streams having a great erosive action on soft rocks, such as underlie this district, are sufficient to account for the effacement of the islands which evidently lay not long ago in these waters. It may also be remarked that the Buzzards Bay River appears to have had a steeper drainage than the other neighboring old streams on the east, which may have accounted for the more complete erosion of the divides

between its branches. It seems, however, more likely that the presence of these shoals in the Nantucket and Vineyard system of sounds is partly to be attributed to the action of tidal currents in this field.

SEAWARD CONTINUATION OF DROWNED VALLEYS.

The soundings given on the coast charts, where the water exceeds about 100 feet in depth, are not in sufficient detail to make it worth while to devote much labor to tracing the probable direction of the ancient drainage channels with a view to ascertaining how near they went to the margin of the continental shelf. We may, however, note certain of the more patent facts.

North of Cape Cod we find a deep channel between Race Point and Stellwagen Bank. The water at the western end of this channel, where it appears to connect with the Cape Cod Bay Valley, has a depth of about 35 fathoms; thence it shoals seaward to about 22 fathoms; still farther to the east it deepens rapidly to about 50 fathoms. The shallowest water in this channel is in the continuation of Cape Cod. Stellwagen Bank has a minimum of 12 fathoms of water upon it, and not much more for its length of about 20 miles; then at the deep channel leading toward Boston Harbor the bottom suddenly declines to the depth of 60 fathoms. The evident suggestion is that Stellwagen Bank is a northward continuation of the Cape Cod divide and that Race Point channel marks the position of a col on the ridge, which was some 70 feet lower than the general surface of the water shed; and also that the Cape Cod Bay River joined what we may call the Boston River near the northern end of the above-named bank.

North of the valley of Boston River another less distinct, unnamed shoal continues the line of Stellwagen Bank in such manner as to suggest that a stream corresponding in a way to that of Cape Cod Bay headed about Cape Ann and flowed southward, joining the Boston River near where that passing from the Cape Cod divides entered it, the united streams flowing on through the Stellwagen ridge to the sea. The general likeness of the outlines of these antithetic valleys, if we may use that name to designate basins of very like character whose streams flow against each other, suggests that they are carved in like materials, or, in other words, that the Cretaceous and Tertiary strata of the Cape Cod district are continued as far north at least as Cape Ann, though they do not appear above the surface. This proposition is made the more probable by the discovery by Mr. Warren Upham of fossils of possible Eocene or Cretaceous age in the drift materials near Highland light. As such remains have not been found elsewhere in the drift of the cape, they have probably been brought from beneath the level of the sea.

Evidences derived from soundings and dredgings in the Bay of Maine indicate, as is well known, the existence of Tertiary and perhaps Cretaceous rocks, at least about the Grand Banks and Georges

Bank.[1] These and other observations indicate that the shoals to the east and north of Cape Cod are probably the remains of ancient divides, and the soundings warrant, in a measure, the interpretation of ancient river valleys, but this task will not here be further essayed.

ORIGIN OF THE CAPE DISTRICT PLATEAU.

An inspection of the contour maps will show that the pre Glacial beds of the cape district, including the islands on the south, have their upper surfaces everywhere at about the same altitude, with a prevailing slope from the western part of Marthas Vineyard, where they rise to about 300 feet above the sea, toward the east and north, declining at Boston Harbor to the sea level, near the end of Cape Cod to a little above that level, and at Nantucket to a height of about 50 feet. The question arises as to the origin of this approximately plane surface. It may be due to either of two actions—to base-leveling or to the leveling action of the sea—or possibly to a complex of these actions. It clearly is inadmissible to suppose that the plateaulike surface is due to the survival of the original stratification surface, for, as has often been noted, the area has been greatly disturbed. Against the supposition that the approximation to horizontality just before the uplift which set at work the streams that cut the valleys of the old rivers of this district was due to base leveling, we may note that this would require us to suppose a very long period in which these much-dislocated rocks had been slowly brought to a level by atmospheric agents. As we see at present on Marthas Vineyard these rocks yield but little to such action. The streams of to-day carry away scarcely any mud; their effect is limited to a slight leaching action. To introduce such a base-leveling period of sufficient duration would call for greater lengthening of the first Pliocene time than it is reasonable to make.

The leveling of this district by the action of the sea might have been accomplished in a relatively short time. The present rate of retreat of the southern shore of Marthas Vineyard is, as before noted, about 3 feet per year; at this rate the sea would occupy 2,000 years in wearing a mile into the land. The width of this table-land, including the submerged portion, being assumed at 50 miles, the leveling process would have required about 100,000 years. Great as this time is, it is probably much less than would have been required to effect the same result by the base-leveling process alone. Here, as elsewhere along coast lines, it is likely that these two actions cooperated, the streams carrying away what they were enabled to and the waves removing the portion of the material which was not thus taken to the sea. It is not likely, however, that the time occupied in the work could have been much less than that above suggested. Here, again, we

[1] A. E. Verrill, Occurrence of fossiliferous Tertiary rocks on the Grand Bank and Georges Bank: Am. Jour. Sci., third series, Vol. XVI, p. 323.

encounter the perplexing difficulty that the history of the beds of the successive epochs in this area requires us to suppose a lapse of time since the close of the Tertiary period much greater than is commonly assumed to have occurred.

POSITION AND CHARACTER OF DIVIDES.

The position of the several divides which mark the limits of the ancient partly drowned valleys of the Cape Cod district is such as would be expected in case the topography of the region had been developed when the surface of the country was at least 200 feet higher than it is at present. The most continuous of these crests is that of the cape itself, extending from the town of Plymouth eastward to Chatham and thence northward to the sand spit which terminates the cape. This divide may have been continued somewhat farther to the east, as will be noted hereafter. The arrangement of the valleys of the headwater streams in this section suggests their former union in two or more valleys, which declined to the north and south. North of the elbow of the cape to the Provincetown sand spit the incutting of the sea appears to have destroyed the original crest of the divide, leaving only the slope of the ridge which drained into the Cape Cod Bay river.

The divide which separates the water of the last-named stream from the upper tributaries of the Buzzards Bay river is still traceable in the long ridge which stretches in an interrupted manner from Monument River to the neighborhood of Plymouth Harbor, terminating in Manomet Hill. It is, indeed, impossible to account for the very peculiar shape of the ground in this district without supposing that it is due to the interlacing of the headwaters of adjacent but oppositely flowing streams. This western divide of the Buzzards Bay valley is continued southward in the united ridge on which the Falmouth moraine lies as far south as Woods Hole. From the harbor of Woods Hole the same divide is shown in a less united form by the line of the Elizabeth Islands to and including the island of Cuttyhunk.

On the south of Vineyard Sound we have in Marthas Vineyard the remains of the other crest of the valley of which the Elizabeth Islands form the other divide. This crest constitutes the northern range of hills of Marthas Vineyard, extending as far east as Vineyard Haven. The central and southern parts of the highlands of the island are on the headwaters of streams which seem originally to have flowed into the Muskeget River valley.

The island of Nantucket appears to be the remnant of several obscure divides, but the greater part of what is left above water is on the slope of the drainage toward the Muskeget and the Monomoy rivers. As will readily be seen, the directions of the ancient rivers in this portion of the district are by no means clear. This obscurity is mainly due to the extensive erosion by tidal currents which has taken place in this part of the field.

It is to be noted that the decline in the altitude of the principal divide of this district, that which extends from Plymouth Harbor to the extremity of the Elizabeth Islands—a distance of about 45 miles—is relatively steep, being from a height of about 300 feet to that of about 100 feet above the sea, or an average of about 5 feet per mile. In view of the considerable width of the valleys in this region, this decline must be regarded as greater than is consistent with the supposition that the region is anywhere near to being completely base-leveled. There is no definite evidence as to the rate of fall of these drowned valleys, but in valleys of such width, cut in materials of so yielding a nature, it is difficult to believe that it could have exceeded 5 feet to the mile. In considering this question it should be noted that the decline of the crest line is not necessarily a true measure of the fall of the valley. In general, however, this decline is, at least in the upper part of the river's course, much less rapid than the fall of the stream. Taking the remnants of the valleys as we find them in Marthas Vineyard, we note that they support the proposition that the bottoms of the old valleys had a slope less than is indicated by their present altitudes. The valleys of the Tisbury and Tiastquan rivers below the points where they are occupied by permanent streams have a fall of about 15 feet in a mile, yet these are the upper and presumably steepest portions of the river systems to which they belong. Although there are no very certain conclusions to be drawn from this inquiry into the slopes of the old rivers of the Cape Cod district, the fact suggests that there may have been some warping movements since the topography was formed.

It is to be observed that the three best defined of the old valleys of this area, those of Cape Cod Bay, Buzzards Bay, and Vineyard Sound, show a certain measure of narrowing toward their lower parts. This feature is most evident in the case of Buzzards Bay, but it is noticeable also in the other basins. This apparently indicates stream erosion working toward the formation of circus-shaped valleys, features which are not uncommonly found in much eroded areas.

In connection with the old valleys of this area the island of No-man's-land offers matter for interesting inquiry. This bit of land, by its position and its relation to the form of the sea bottom, suggests that it is the remnant of the southern divide of a valley the stream of which drained into Vineyard Sound river near Gay Head. The shoal about this island, though it is evidently subjected to much erosion by the strong current and waves, indicates that the isle, which is rapidly wearing away, was originally of much greater extent than at present. The retreat of its shores, which appears to be going on at the rate of about 3 feet per annum, will bring about its destruction in less than a thousand years. Its place will then be for a time occupied by a shoal which, under the cutting action of the waves and tidal currents, will be planed down to a considerable depth, coming finally to the state of the shoals in Nantucket Sound.

TRESPASSING OF RIVERS.

The position of the several divides between the ancient basins of the Cape Cod district indicates that the streams had advanced far in the development of their topography before the last great subsidence. Here and there we find evidence that the crests had been brought to rather sharp edges, having in most cases lost all trace of the original table-land character which seems to have been in some way impressed on them before the last invasion of the valleys took place. The Cape Cod crest was evidently sharp; so, too, was that of the Elizabeth Isles. That of Marthas Vineyard was of a more complicated nature, retaining much of the original table-land form.

The process of stream capture, of which there are good instances on Marthas Vineyard, which evidently took place before the last great downsinking that brought about the formation of the bays and sounds, shows that the adjustment of the topography about the heads of the streams on that island had not been anywhere near completely effected. Similar though less evident indications of such action on the mainland may be found in the valleys of Monument, Bass, and Pamet rivers, where streams had evidently in good part or altogether cut back through the divides, more or less invading the drainage of the antithetic stream. In two of the last-mentioned instances, Monument and Bass rivers, the transgression seems to have been made by streams flowing southward toward the valleys of the Nantucket Sound area. In that of Pamet River the slope seems to have been to the westward into Cape Cod Bay. The passages between the Elizabeth Isles were apparently much as we now find them before the close of the time preceding the last deep submergence. If this be the case, the head streams of either the Buzzards Bay or the Vineyard Sound river may have crossed the divides, and as these passages have been much changed by glacial action and by tidal currents it is not easy to determine in which direction the trespassing waters flowed.

As the valleys now occupied by the bays were evidently rather deep, probably at least 500 feet at their deepest part, below the higher parts of the divides, the incomplete nature of the topography on and near the crests is no good reason for supposing that their bottoms were much indented. It is a very common feature of river valleys to have their lower parts level and their upper parts deeply indented. We thus are not compelled to suppose that a great deal of filling has been necessary in order to bring about the general approximation to horizontality exhibited in the bottoms of the bays.

AMOUNT OF SEDIMENTATION SINCE THE PRESENT LEVEL WAS ESTABLISHED.

As noted under the last heading, the fact that the bottoms of the Cape Cod system of bays and sounds are approximately level can not be taken as evidence of any great amount of sedimentation since the sea attained to about its present position at the end of the last important down-sinking. A close study of the form of these bottoms, based on the soundings of the United States Coast Survey charts, shows a multitude of slight irregularities which can not well be attributed to the differential deposition of sediments due to tidal currents, but can best be explained by supposing that the layer of imposed detritus is not yet thick enough to completely mask the preexisting ridges and valleys of these submerged areas.

If there had been a great amount of deposition on the sea floor in the Cape Cod bays we should expect to find all the original irregularities of surface due to their erosion quite effaced, in the manner in which it appears to have been destroyed on the great southern plain or on a lesser scale on the morainal plain of Marthas Vineyard; but while there are traces of such depositional shelves near the shore, as on the southern coast of the last-named isle and along the south and east shores of Cape Cod, these shelves are narrow and flat. In form they evidently are quite unlike the bottoms of the water areas at a distance of 2 or 3 miles from the coast line. The evidence from soundings goes to show that the migrations of sand in these areas are locally considerable, but they appear to occur only in the paths of relatively strong tidal currents, such as sweep through the sounds and in the bays; it is to the effect that, notwithstanding all the coastal erosion which is going on, the contribution of sands to the bottoms of the bays at the distance of a mile or more from the shores is very slight in amount. These facts lead me to doubt whether as much as an average of 50 feet in depth of detritus has been accumulated on the floors of the bays since they last came below the level of the sea.

On the south side of Marthas Vineyard and of Nantucket and on the east side of Cape Cod the considerable invasion of the land by the sea has doubtless done much to contribute material for sedimentation, but in Cape Cod Bay and Buzzards Bay the erosion of the shores has not been sufficient to supply more than a few feet of detritus over the floors of the basins. The waste of organic life deposited in these basins is relatively small in amount, being much less than in those parts of the shores and shallows to the northward, where mollusks and seaweeds are more abundant.

Owing to the situation of the Cape Cod salient it is not in a position to receive detrital materials from a distance in the manner in which they are accumulated along the shore south of New York. North of the cape the deep trough passing outward from Boston Harbor inter-

cepts the current and wave driven waste coming from the northern shore. On the southwest there is no set of currents driving such material toward the waters of the sounds and bays. Some contribution may have been had from the wreckage of islands now reduced to shoals, but it probably has not been in large amount.

DEPTH BENEATH SEA LEVEL AND NATURE OF THE CRYSTALLINE ROCKS IN THE CAPE COD DISTRICT.

At no point in the district of Cape Cod are the ancient crystalline rocks exposed to view, nor does the drift covering on any part of the land indicate by its character that these deposits are on the land areas, at least near the surface. In passing from the mainland toward the cape we find the nearest localities of the crystalline rocks at Plymouth Harbor and on the west shore of Buzzards Bay. Throughout the southeastern section of Massachusetts these rocks exhibit a gentle and tolerably uniform slope toward the base of the cape at the rate of about 20 feet to the mile. This would place the old granite series at the level of 100 or 200 feet below the sea level on the eastern shore of Buzzards Bay and at a depth below that plane of about 1,000 feet at Chatham Harbor. Inasmuch, however, as all this region has been greatly disturbed, and as the disturbances most probably included extensive movements of the ancient rocks as well as of the Mesozoic and Cenozoic strata which rest upon them, no great value can be given to these estimates.

On Marthas Vineyard and scantily on the shores of the southwestern portion of Cape Cod, particularly along the southeastern side of Vineyard Sound, as before remarked in the account of the glacial drift, a great quantity of chalcedonic quartz pebbles are found. So abundant are these coarse agates that hundreds of tons of the material could at times be gathered along the shore. It is evident that these fragments have been glacially transported, and, as is indicated by the character of the layer of erratics as well as by the glacial scratches, the movement of the ice was from the northwest, if indeed it was not from a point nearer the west. Nowhere on the mainland are rocks of this nature known either in situ or in the drift. Along with these chalcedonic erratics go great quantities of pebbles of white-vein quartz of an aspect quite different from any known on the shores to the northward. A close comparison of the pebbly materials on the islands of the Cape Cod district with the rocks on the mainland will undoubtedly show other cases of this kind. On the body of Cape Cod, in increasing proportion as we go from Monument River eastward, we find groups of vein and volcanic materials differing in nature from those on the neighboring islands. In this last-mentioned district the pebbles of volcanic rocks are very abundant, especially in and beyond Orleans.

The evidence afforded by the erratic materials of this district shows

that just to the seaward of the shore line there is both to the north and the south of Cape Cod a belt of rocks which have been the seat of great volcanic and solfataric action, and that these deposits have been much metamorphosed. In this connection it may be noted that a belt of disturbance of the nature indicated on the sea bottom about Cape Cod begins in the region about the Bay of Fundy and extends parallel to and partly within the shore along the coast of Maine. I have noted the occurrence of such conditions in the published accounts of work done for the Survey in the districts about Passamaquoddy, Cobscook, and Orange bays, and in the district of Mount Desert and on Cape Ann. In the two first-named fields the presence of distinctly volcanic deposits is well proved. At Cape Ann evidence of true volcanic action is lacking, but the extraordinary amount of dike injections, which evidently increases as the shore is approached, shows the effect of the same system of disturbances. It thus appears probable that the coast line of this continent, from the head of the Bay of Fundy at least as far to the southward as the mouth of Buzzards Bay, lies upon the inner margin of a tract which has been greatly subjected to volcanic and solfataric action. It is not improbable that the indentation of the first-named bay may be due to the subsidences connected with these disturbances and that the position of the coast line on this part of the shoreland is to be accounted for either by the downward movement or by the relative ease with which the coastal fringe of rather incoherent deposits were eroded by the sea. Interesting as these questions are, they can not be followed further here except to suggest that the volcanic areas of the Boston Basin, of the Connecticut Valley area, and of the region in and near the lower part of the Hudson Valley, where there is reason to suspect that the volcanic rocks are newer than the Newark beds, are within the limits of this marginal fringe of such deposits.

FOSSILS DREDGED FROM SEA FLOOR NEAR CAPE COD.

From time to time there have been reports that fossils of a character which would indicate that they came from beds such as are found on Marthas Vineyard or at Marshfield existed on the sea floor to the north and east of the cape. These specimens have been brought up on anchors or by the dredge. It seems likely that in all these instances the materials have been derived from the drift deposits on the floor of the sea, though it may be possible that, as about Georges Bank, the considerable energy of the tidal currents may scour away the soft parts of the bottom, leaving the harder fragments as a coating on the sea floor.

The evidence above referred to, though fragmentary, and at best not very trustworthy, is enough to show that to a considerable depth, say to 200 feet or more, the bottom is, in part at least, occupied by the fossiliferous deposits which were here and there exposed in the cape district just before the Glacial period. This serves to show that the

erosion which took away so large a share of the later pre-Glacial accumulations—those designated as the Truro and Weyquosque series or the Barnstable clays—affected a large extent of the sea bottom for a considerable distance out to sea. Without attaching too much importance to this obscure evidence, it may well be taken as of some value in showing that the region was for a long time elevated to the height of 200 feet or more above its present level, or, what comes effectively to the same thing, that the sea was at about that depth below its present plane. Thus the considerations going to show a recent submergence, which are derived from the topography of the coast and the drowned valleys, has some support from the evidence which these chance samples of the bottom afford.

It has been suggested that these fossils brought up by dredging may be from the drift deposits which are presumed to exist for some distance to the east beyond the shore. Against this hypothesis may be set the fact that fossils of the Cretaceous and Tertiary beds have rarely been found preserved in any glacial deposits, even where those beds lay immediately upon the strata richest in organic remains. The probability that they would thus occur in quantities sufficient to account for the numerous chance finds is so small that it may be disregarded.

TIME RATIOS INDICATED BY POST-TERTIARY PRE-GLACIAL EROSION.

It is not possible, in the present state of our knowledge, to undertake any final essay in determining the time occupied in the erosive work done in this region since the close of the Pliocene epoch. It is, however, possible to give some general and relative indication of these durations.

The facts show that after the deposition of the Pliocene deposits of Marthas Vineyard a vast erosion occurred, which shaped the strong topography that is exhibited in the western part of that island. In the present condition of that area, though the valleys are deep and much of the surface is but slightly drift covered, the rate of stream erosion is almost nil. Even in times of heavy rain the brooks show hardly a trace of color due to other than the stain of decayed vegetation. In the period before the deposition of the drift the rate of wear was probably more rapid than it is at present, but it is impossible to estimate the value of this difference. We are therefore left to mere impressions as to the time required for the development of this topography. These inferences, however, are of some importance.

It is in the first place to be noted that the rocks of this region are, and have been from the time of their formation, very open-textured. They readily absorb the rain water, which cuts no channels on these areas, which are so nearly driftless that the Cretaceous and Tertiary deposits are essentially at the surface. This must have made this field, with any rainfall, which was not very much greater than that of to-day,

one of slow erosion, for the reason that the waters entering the ground would have been discharged, as they now are, at the level of the permanent streams and in a very gradual manner. This action may now be seen in fields of great extent, as in the town of Chilmark, or near Gay Head. Nor can we suppose that the water penetrating to the depths exercises any considerable solvent action. The strata which it traverses contain very little soluble matter, and the springs—save that they sometimes exhibit the results of decomposing pyrites in the sulphureted hydrogen they give off and contain a considerable amount of alumina sulphate—are essentially pure. The facts above noted lead to the conclusion that the erosion of the Vineyard area has from the beginning been slow.

On the basis of a slow erosion we have to account for the formation of river valleys a mile in width and having a depth of from 150 to 200 feet, as well as for the renewal of an unknown section which has been worn away from the crests of the hills. Assuming that the average ablation of the area has been at the rate of 1 foot in one thousand years, a rate which must be accounted rapid—it is equaled, so far as ascertained, in no part of the world which bears a covering of natural vegetation—in that it would at this rate of cutting require somewhere near 200,000 years to carve out these valleys; but, as is easily seen, the valleys are only a part of the result of the erosion which the streams have applied to them. The elevated country between these troughs has also gone down, so that it does not seem unreasonable to assume that the total erosion of this valley-making period has required 300,000 years.

Beyond the clear evidence of a long erosion interval afforded by the valleys of Marthas Vineyard we perceive that there is an unmeasured and perhaps immeasurable time which intervened between the period when the rocks in which the depressions exist were dislocated and that when valley-making began. It seems tolerably evident that in this period the sea stood some hundred feet higher than it does at present and that the surface was gradually base-leveled until it came nearly to the plane indicated by the highest land of the island. This little-indicated period of erosion, the sole evidence of which is found in the faint yet distinct marks of an ancient plain, antedating the formation of the present drainage system, possibly represents a duration several times as great as that shown by the action of the streams which now are at work.

In a general way following the development of the valleys of Marthas Vineyard and those which were formed in the tilted deposits of Cape Cod, came a period of deposition in which the various beds of Nashaquitsa, Barnstable, and Truro series were laid down. The history of this stage or stages in the development of the cape district is not yet unraveled. These several sections may all be of the same age or they may represent, to a greater or less extent, the history of

successive periods. However this may be, there can be no doubt that the time occupied in the deposition of these beds was very great, and that the detritus which was accumulated came in part, if not altogether, from areas north and west of the cape district, as is shown by the fact that the beds in question to a great extent mantle over the ancient topography and rise to near the level of its highest elevations.

Following the accumulations of the Truro-Barnstable groups came the third great period of aerial erosion in this field. During a period of elevation which brought the land to a level at least 200 feet higher than it is at present, the erosive work of the streams cleared away the deposits of stratified sands, clays, and gravels from the valleys which it encumbered, and extended the denudation of those broad and thick sheets of strata until only remnants of the original mass remained. The amount of erosion effected during this period immediately antedating the last ice epoch can not be gauged, for the reason that the greater part of the area in which it was effected is now submerged beneath the sea; but it was clearly much greater than that which was done in the time to which we owe the development of the several valleys of Marthas Vineyard or the like troughs of Cape Cod. To it we owe not only the general clearing out of those troughs, but the excavation of the river basins which are now marked by the bays and sounds of southeastern Massachusetts.

In considering the time required for the formation of the later stratified deposits of the Cape Cod district we have first to note that the accumulation of these beds indicates a long period of erosion, the record of which, as before remarked, is not found in this area for the reason that it was then beneath the sea. As the work done was of sufficient magnitude to form a broad sheet of detritus, extending from some point far inland, probably the central highlands of Massachusetts, to and beyond Truro and Nantucket, having a thickness on the average of not less than 100 feet, and perhaps several times as great, it is evident that the time occupied could not well have been less than that attained for the second erosive period—that which shaped the greater valleys of Marthas Vineyard. The last great erosion period—that which morcellated the stratified deposits which overlapped the old mountain-built beds—appears to have required more time than any of the earlier periods of wearing. The valleys were brought to a great width. Nearly all the deposits of the last formations were removed, leaving only fragments of them on or near the divides. As this work was done mainly on very permeable beds, into which the rain penetrates rapidly without developing small, superficial streams, the work of wearing could not have proceeded with great rapidity.

The facts as above presented lead to the conclusion that since the close of the Tertiary period, or perhaps from some time after the end of the Pliocene epoch and down to the advent of the ice in the last Glacial epoch, there have been four tolerably distinguishable periods of erosion

in this field, each requiring a time the duration of which, even in a geological sense, must be accounted as long. Various estimates, made on the basis of the present rates of erosion, lead me to the conclusion that this interval was not less than one million years.

Without attaching any definite value to the reckonings as to the durations of the periods in which the wearing down on this district was effected, it may be claimed that no geologist who has attentively considered the problems of time ratios in erosion is likely, on a careful study of this field, very much to reduce this estimate. Although the assumption of something like a million years for the interval between the end of the Tertiary and the beginning of the last ice epoch is not in accordance with the views as to the time ratios in the later stages of geological history which were entertained down to the beginning of this decade, it is becoming evident that the old view as to the brevity of this interval was hastily taken and will have to be revised. It is in order to bring this point into debate that the previous estimates as to the time occupied by the completed succession of actions which have taken place in post-Tertiary pre-Glacial time are here submitted.

It may be remarked that the prejudice in favor of a brief time since the close of the Tertiary period has rested in part on the fact that the amount of consolidation which has taken place in the deposits of that portion of the earth's history has been in most cases small. It is, indeed, difficult to believe that beds which have been as little changed as the strata of this age usually are have been formed for millions of years. When, however, we note that in Mesozoic rocks, and even in those of the Paleozoic sections, the amount of alteration is often slight, we can well understand that these more recent deposits, which have not undergone deep burial, have survived for ages without essential change.

SUMMARY AND CONCLUSIONS.

The results of the observations noted in the preceding pages of this report justify the following statements relating to the Cape Cod district, and particularly concerning the peninsula of that name.

After the erosion of the Cretaceous and Tertiary beds disclosed on Marthas Vineyard, several series of sedimentary deposits were laid down. The first of these deposits, which may fairly be reckoned as of early Pleistocene age, though deposited in horizontal attitudes on the disturbed older beds, were in turn somewhat stressed, the resulting dislocations being relatively much less considerable than those which affected the Cretaceous and Tertiary deposits. These dislocations are evident not only on Marthas Vineyard but throughout the area of Cape Cod between Woods Hole, Bourne, and Highland Light. They also extend up the coast at least as far as Plymouth Harbor; their western extension is not yet determined.

The post-Tertiary deposits just referred to appear to be divisible into two groups, the lower of which is exhibited on Marthas Vineyard and

in Cape Cod as far north as Monument River and eastward to Orleans. This series is characterized by the presence of red clays and sands, which appear to owe their origin to the decomposition of Tertiary strata such as occur at Gay Head. Apparently above these beds, which have been termed the Nashaquitsa series, occurs another series, here known as the Truro. The characteristic of these beds is that they plentifully contain a fine, white, floury, micaceous sand, which is very much decayed. These sands are combined with coarser arenaceous materials and occasionally clay beds, the clay being of the ordinary grayish or yellowish hue. So far as is ascertained, these beds contain no pebbles of compound rocks, the pebbles, indeed, being very rare and, so far as observed, of quartz, and always small. The Truro series has not disclosed any materials apparently rising from decomposition of the Tertiary beds. It is possible, but not probable, that the Nashaquitsa and Truro series should be regarded as one group. The distribution of the beds, however, is against this view.

The group of brick clays known as the Barnstable series appears to have been laid down after the Nashaquitsa and before the Truro beds had been formed and dislocated. The evidence as to this succession, however, is not perfectly clear.

During the deposition and erosion of the series above noted the Cape Cod district has been subjected to a number of movements of elevation and subsidence of which the imperfectly interpretable changes are shown in fig. 87, p. 522. These movements indicate very remarkable instability in the position of this portion of the continent from Jurassic time to the present day, but the alterations of level appear to have been limited, so far as determinable, to a range not exceeding, perhaps, 1,000 feet. It is to be noted that these accidents appear to increase in frequency as we approach the present day. This, however, is most likely due to the fact that the records are more complete and interpretable as they come toward the present time; possibly, also, as my colleague, Mr. J. B. Woodworth, has noted to me, for the reason that the later records are more coastal in their nature than are those afforded by the earlier deposits. It is to be remarked as a very significant feature that the series of deposits from and including the Nashaquitsa to the close of the Barnstable series have afforded no fossils. It is possible, but not probable, that fossils may have been contained in these beds, the remains having disappeared under the very free leaching which has occurred throughout this area, where the rocks are extraordinarily porous.

It is possible, and perhaps probable, that these beds, in part at least, represent deposits in advance of glacial sheets. Nevertheless, as we have to suppose that in part the materials were laid down in salt water, it is not easy to understand the complete absence of organic remains, which, as we know from other fields, even those near by, as on Nantucket and on the coast of Maine, contain abundant fossils. Moreover,

it is difficult to believe that during the extended topographic changes which occurred while the three series above mentioned were depositing, and also during the period of dislocation, which is marked in the attitude of the beds, no ice could have remained near enough to the district to affect the character of the sediments. Still further, the absence of erratic rocks in the Nashaquitsa and Truro contraindicates the action of ice.

The condition of the deposits contained in the series of the Cape Cod district, formed after the close of the Tertiary and before the advent of the glacial sheet, indicates the rapid erosion of an area of crystalline rocks which had previously been affected by a deep decay. It is conceivable that this erosion, acting on softened materials, was due to rivers, but the general absence of vegetable matter in the deposits makes it perhaps more likely that the work was accomplished by glacial erosion occurring during the periods of subsidence which are indicated by the sections.

The facts stated in the preceding pages of this report make it clear that the post-Tertiary and pre-Glacial history of southeastern Massachusetts is much more complicated than has hitherto been supposed. The interpretation of the record which has been given must be regarded as in a great measure tentative. A further development of our understanding of the facts will doubtless be attained when the related deposits on Long Island, New York, have been explored. There is reason to hope that in that field may be found the passage from the conditions of southeastern New England to those accepted in the related Columbian beds and other recent deposits in New Jersey and the portions of the coast to the southward.

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